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TECHNOLOGY ASSESSMENT OF FUTURE INTERCITY PASSENGER TRANSPORTATION SYSTEMS

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Volume 3
Technological Characteristics of Future Intercity Transportation Modes

TECHNOLOGY ASSESSMENT OF FUTURE INTERCITY PASSENGER TRANSPORTATION SYSTEMS

VOLUME 3

TECHNOLOGICAL CHARACTERISTICS OF FUTURE INTERCITY TRANSPORTATION MODES

Prepared by

A TECHNOLOGY ASSESSMENT TEAM

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and
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The views and conclusions presented in this report are those of the staff of the Technology Assessment Team and do not necessarily reflect those of NASA or DOT.

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R. S Shevell
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Study Objective

Although technology assessment involves a great deal more than the study of technology, it is necessary to have a clear understanding of the technological possibilities in the future in order to appraise the impacts of such technology. In this study, we are involved with transportation technology, and this report presents overall and specific information about the technological characteristics of present, future, and possible future technological forms of transportation modes.

It is well to recall the meaning of the word "technology." Technology is defined in Webster's Third New International Unabridged Dictionary as

> *"1. the terminology of a particular subject· technical language 2a· the science of the application of knowledge to practical purposes. applied science [the great American achievement has been . . . less in science itself than in ~ and engineering--Max Lerner] b(1)· the application of scientific knowledge to practical purposes in a particular field [studies are also made of polymeric materials to dental ~ --Report. Nat'l Bureau of Standards] (2) a technical method of achieving a practical purpose [a ~ for extracting petroleum from shale] 3 the totality of the means employed by a people to provide itself with the objects of material culture "*

The emphasis is on the practical application of science and the "totality of the means employed by a people to provide itself with the objects of material culture." Since the limitations of the ability to provide are both technical and economic, any discussion of technology must include economic factors, both on an absolute basis and in comparison to alternative means of satisfying a need.

The report deals with transportation technology on two levels. The first level is an exploration of the technological possibilities foreseen for the year 2000 and immediately beyond. All transportation modal possibilities are discussed and their general characteristics tested and evaluated. The judgment is then made as to which of these technologies will bring to transportation those qualities required by society and therefore are likely to be viable candidates for the time period

concerned. For these likely modes detailed technical, economic, and environmental characteristics are given

For rapid reference, the second section of this report consists of brief summaries of the nature, development status, and basic characteristics of each modal variation. Also noted is the type of mission most suitable for each modal variation, i.e., commuter, short range, long range, etc. These are followed by separate sections on air, rail, high-speed guided ground transportation and highway modes. In each of these sections, descriptions of the future characteristics are given for each technological form in some depth, followed by detailed technical characteristics and economic characteristics of those modes found likely to share an important role in the year 2000.

Long-Range Technology Forecasting

As for projection to a point 50 years from now. the year 2025, relatively little can be offered One can gain a perspective on this problem by thinking back to 50 years ago, in the year 1925 At that time, few people could afford the relatively primitive automobiles. Transport aviation was almost nonexistent and was mostly the province of a few people looking for a thrill at high cost. The rail system was the dominant transportation mode Examining many other phases of life in 1925 such as communication, home management, merchandising, accounting practices, and general scientific and mathematical knowledge and application, one can quickly perceive how impossible it was to predict today's world Developments in electronics, materials, and all branches of engineering have led to computers, television, satellites, home appliances, the automobile, and the airplane in forms completely unforeseen in 1925 The major reason why these things could not have been foreseen was that these devices required inventions, inventions such as television, the transistor, integrated circuits, the gas turbine engine, wing sweepback, and automated production processes which have permitted mass production of affordable technological products. Realistically looking at the ability to predict 1975 in the year 1925, one is quite humbled as to the prospects of predicting the year 2025 from the year 1975. Fundamentally, it requires the ability to perceive inventions and if any of us were smart enough to perceive the invention we could just go ahead and invent it right now Therefore, there is little but brainstorming that can be done over the 50-year period.

Reviewing the development of technology over the last 25 years, one can find almost as many developments, expected by technically sophisticated seers, which failed to achieve a viable status, as there are devices that are now important and were not visualized. In other words, the business of being a forecaster has risks as great in positive thinking as it does in negative or unimaginative thinking. In the airplane field alone, going back 25 years, we can find concepts such as laminar flow control, nuclear aircraft, supersonic transports and STOL (short takeoff and landing) which many aeronautical specialists thought would make a

very substantial impact by 1975, but which can now be seen to require significant technical development or even invention to achieve practical and/or economic realization.

Some Thoughts on Research and Development

It is important to avoid confusing the "most-likely transportation modes" and desirable future research. Research is intended to create new knowledge which may contribute to the development of an economically viable system with desirable service and performance characteristics. One never knows in advance what the results of research may be. Although certain technological developments may be less likely to become operational based on current information, technological breakthroughs or inventions may change the feasibility of these concepts. For example, propulsion advances have usually paced aeronautical progress and may again, particularly for the supersonic transport (SST). In 1947, jet transport studies* showed maximum ranges of about 750 statute miles and poor economics. Sweepback was a threat to flying qualities. Many were fearful of the pressurization of passenger cabins at altitudes above 30,000 feet. Twelve years later jet transports revolutionized travel.

Nevertheless, recognizing all of this does not necessarily lead to optimism regarding certain aircraft or ground transportation forms, as discussed in this report. On the other hand, basic research in all transportation areas should be continued and constantly reviewed. The results of research may bear fruit in unexpected ways.

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*Richard S. Shevell, "Operational Aerodynamics of High Speed Transport Aircraft," *Journal of the Aeronautical Sciences*, Vol. 15, No. 3, March 1948.

II. SUMMARIES OF TECHNOLOGICAL ALTERNATIVES FOR VARIOUS TRANSPORTATION MODES

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Stanford University

II. SUMMARIES OF TECHNOLOGICAL ALTERNATIVES FOR VARIOUS TRANSPORTATION MODES

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II. SUMMARIES OF TECHNOLOGICAL ALTERNATIVES FOR VARIOUS TRANSPORTATION MODES

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Introduction

Knowing that there were hundreds of intercity transportation technological forms or variations in which the guideway, suspension, propulsion, energy requirements, pollution, noise, or other characteristics differ, the technology team chose to separate modes first into general classes such as air transportation, rail transportation, high-speed ground transportation, and highway transportation. We did not want to omit a mode just because, at this time, it seems strange compared with other modes. In the future, there might be a demand for a mode that optimized a particular quantity or quality, even though it was technically or economically less competitive. On the other hand, economic characteristics play a large role in determining the acceptance of a transportation mode.

Economic competitiveness of a mode is highly dependent on certain parameters of demand and range. For example, below 100 miles, commercial aircraft are doubtfully competitive with the automobile. Further, it was evident that the automobile and its progeny of the future, which might have a different propulsion system, etc., by the year 2000, still had a very distinct place for the short range, low demand market and that it would probably always be so even though the technical details would change. High-speed ground transportation (HSGT) has a large capital cost so that a high passenger demand is essential if economic viability is to be approached. The greater the distance, the more important is high speed, so that ground modes are less competitive at long range.

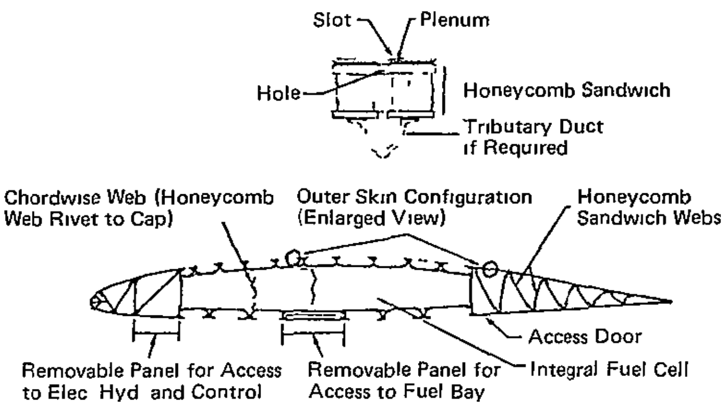
In this section, a brief summary of each modal possibility is given. Included are the essential technological characteristics, their advantages and disadvantages, and the technical advance or breakthrough, if any, required for the economic implementation of the mode.

Where sufficient data exist, a comparative cost factor (CCF) is given. The CCF is a relative value based on the fare required to cover all costs including direct and indirect operating costs and, where not included in these factors, amortization of infrastructure costs. The value of the CCF is selected as 1.00 for future transport aircraft in the 1990s with a passenger capacity of 200 operating over a range of 1,500 statute miles (2,420 kilometers). A CCF of 0.5 would indicate a cost half as large as for this aircraft, while a CCF of 2.0 would show twice that cost.

A listing of possibly competitive modes in each mission class is given.

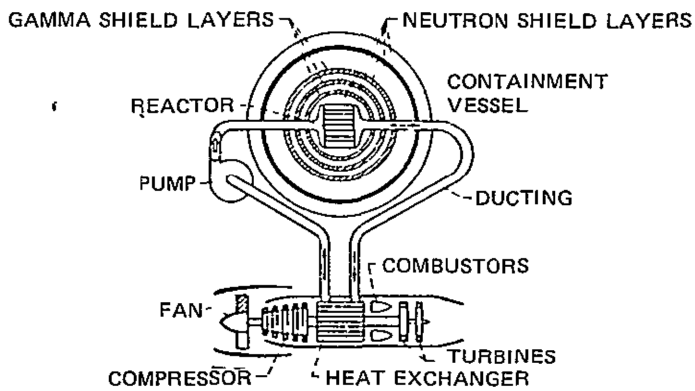
Air Transportation

- Laminar Flow Control--Large reduction in skin friction drag obtained by continually removing boundary layer by suction through holes or slots over most of the surface of wings and bodies, potential reductions of 15% to 20% in fuel, 10% in direct operating cost; concept proven in wind tunnel and carefully run flight tests, very sensitive to dirt and insects and therefore has never been operationally practicable. Requires unknown solution to latter problem to become feasible.

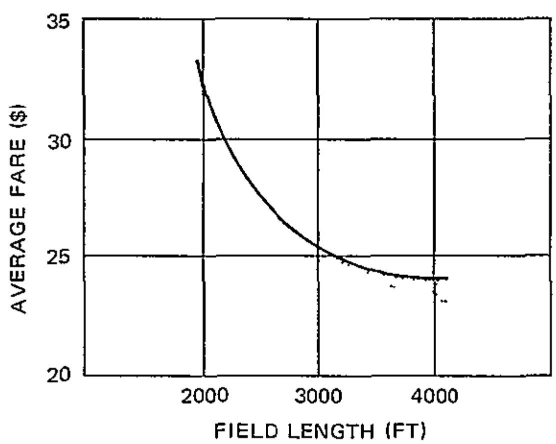


Slotted Suction Laminar Flow Wing Northrop X-21 Airplane

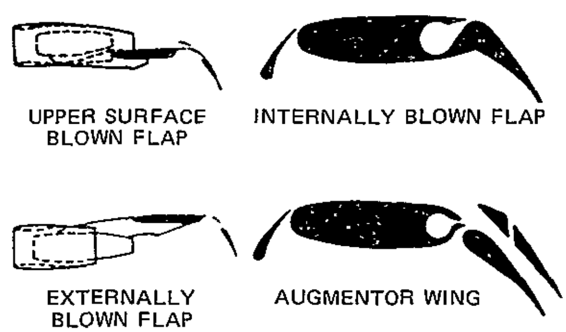
- Nuclear Powered Aircraft--Nuclear power plant eliminates use of fossil fuel, permits infinite range, extremely high shielding weight makes minimum feasible airplane weight very high--1,500,000 pounds. Based on present knowledge, operating costs as cargo carrier are very high at least up to very large weights above 2,500,000 pounds. Potentially severe environment problems in case of accident to aircraft will have to be resolved. Subsonic speeds.



- Short Takeoff and Landing (STOL) Aircraft--Utilize propulsion system to substantially increase lift and permit short takeoff and landing distances; can be operated from small airfields, have higher operating and investment costs than conventional aircraft as well as higher fuel usage, advantages due to close-in airport potential severely restricted by environmental problems, economic and energy disadvantages probably will prevent commercial usage except in special circumstances, e.g , mountain recreational air strips. Speed range from Mach number 0.6 to 0.8.

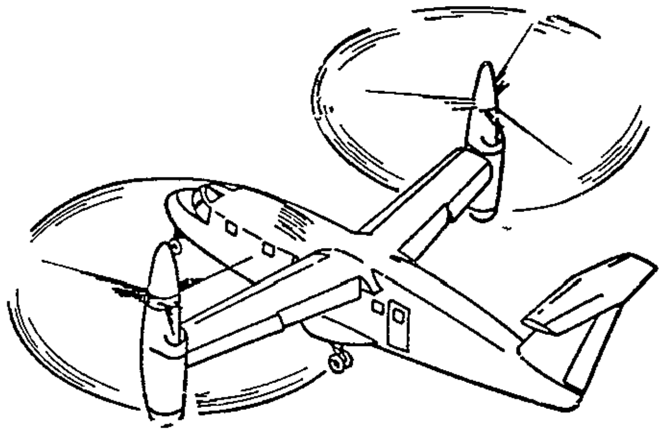


Fare vs Design Field Length in the California Corridor for Quiet Propulsive Lift Aircraft (1972 Dollars)

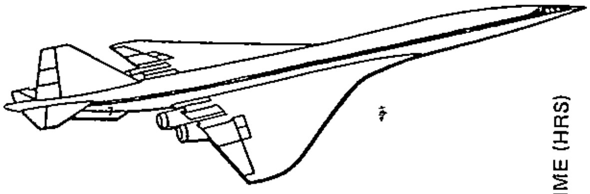


Alternative Propulsive Lift Systems

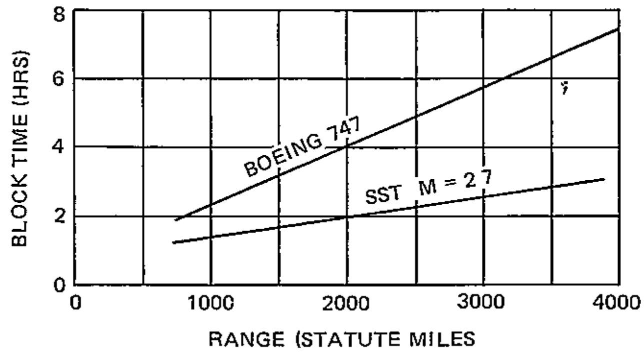
- Vertical Takeoff and Landing (VTOL) Aircraft--Rise and descend vertically, permits small operating land space. Only present commercial operating type is the helicopter. High costs limit usage to very short ranges. Various new types under development will increase cruise speeds and may reduce costs; most promising is the tilt rotor, although its costs and technical problems are not yet established.



- Supersonic Transports--High cruise speeds, two to three times faster than sound, trip times reduced by 45% to 55% on transatlantic ranges. Present Concorde aircraft have direct seat-mile costs triple and total costs double those of present wide-body subsonics, fuel usage three times as high as subsonics. Second generation SST with today's technology would have direct costs considerably less than double and total costs and fares 40% to 50% higher than 747; fuel usage 2 to 2.5 times as great per seat-mile. Sonic boom problems would have to be resolved by currently unknown means to permit domestic use. Sonic booms and current estimates of costs indicating high break-even fares will limit market, requires huge development investment beyond scope of private industry, requires major breakthrough in propulsion (e.g., variable cycle engine) plus gains in aerodynamics and materials to compete economically. Also needs intense engine development to reduce nitrogen oxides in exhaust because of serious upper atmosphere ozone layer threat.

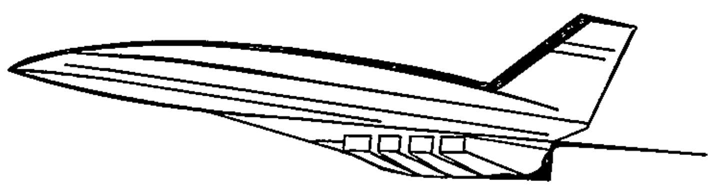


Boeing 2707 Supersonic Transport

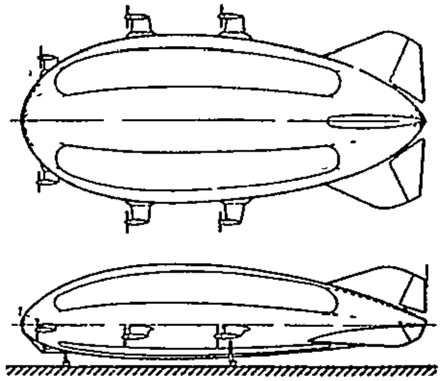


Comparison of Block Times for the Boeing SST and 747 Airplanes

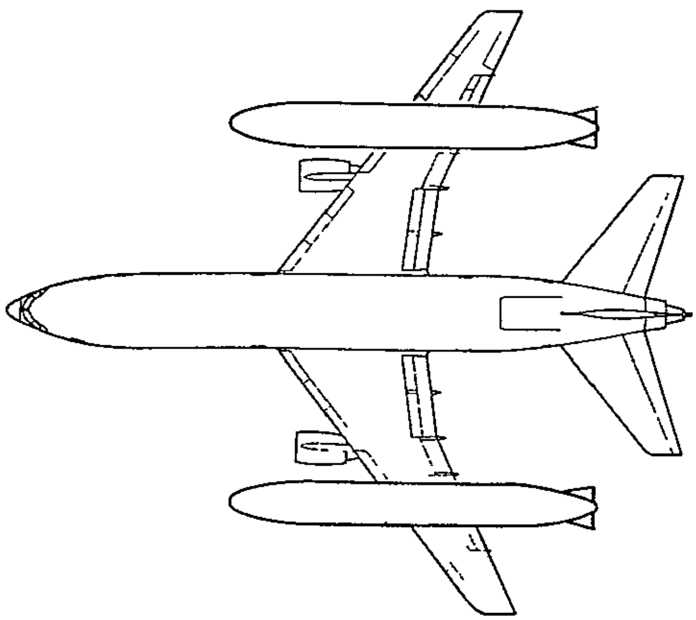
- <u>Hypersonic Transport</u>--Cruises at speeds five to eight times that of the speed of sound, requires enormous technological development beyond the SST involving dual mode (turbojets plus ramjets) propulsion, cryogenic cooling probably using liquid hydrogen as a coolant and a fuel, stagnation temperatures of about 2000°F which pose critical structural problems especially since liquid hydrogen must also be contained, severe environmental problems, such as nitrogen oxides in the upper atmosphere, are even more difficult to solve than for the SST due to very high ramjet engine temperatures. Also has sonic boom problem especially during climb and acceleration. Operating costs are probably quite high and very dependent on liquid hydrogen costs. Requires enormous research and development breakthroughs.



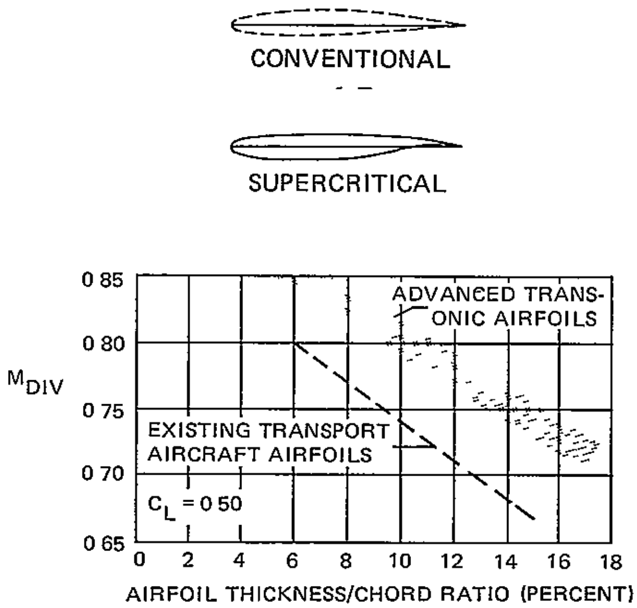
- <u>Lighter-Than-Air</u>--Buoyant lift provides near vertical takeoff and landing capability, low fuel consumption. For scheduled transportation of passengers and cargo, provides low speeds at high cost; may have application in very short-range airport feeder operations, although studies indicate little buoyancy compared to dynamic lift is desirable, potential for "remote-lift" and "aerial platform" applications.



- Hydrogen-Fueled Aircraft--Uses liquid hydrogen fuel which has 2.8 times as much heating value per pound as jet fuel but requires 3.8 times the volume. Can be applied to any speed aircraft and is a requirement for hypersonic flight. For a given mission, fuel weight is much less, but high fuel volume lowers lift/drag ratio. Result is much lower takeoff weights and slightly lower weight empty. High hydrogen costs make overall operating costs high. Liquid hydrogen requires all new fuel supply system. Advantage is freedom from fossil fuel but this is only attained by using 4.9 British thermal units (Btu) of nuclear heat output to produce 1 Btu of liquid hydrogen by electrolysis. Hydrogen can also be produced from coal but at higher cost than producing jet fuel from coal. Requires cheap unlimited source of energy to become valuable.



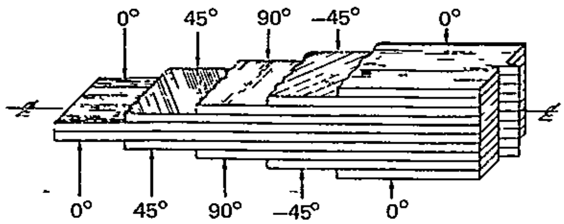
- Advanced Technology Subsonic Transports--Provides current speeds (±10%) with less fuel consumption (30% below widebody transports) and lower seat-mile cost (-12%); utilizes improved transonic airfoils which permit thicker less-swept wings at any design speed thereby saving structural weight, composite materials (graphite or boron fibers in an epoxy matrix) which save significantly in structural weight, active controls which permit reduced stability and thus save tail surface drag and weight, some modest propulsion efficiency gains, possible small aerodynamic improvements such as winglets, and designs



Advanced Transonic (Supercritical) Airfoil Performance

optimized for high fuel costs, i e., higher aspect ratio (span). Logical next generation aircraft Requires extensive service tests of composite materials to prove acceptable life characteristics.

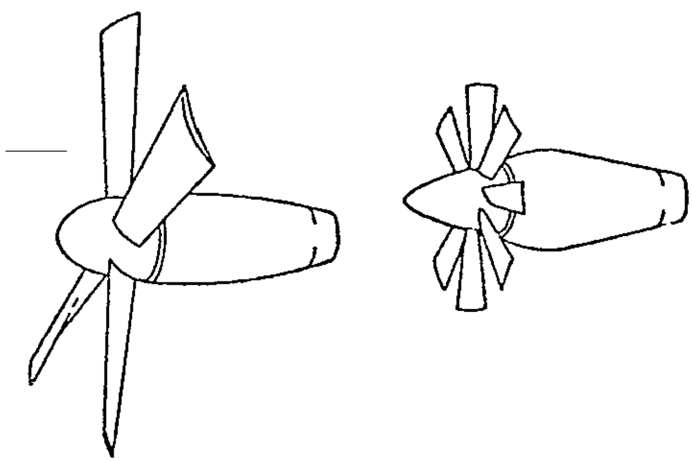
Range (statute miles)	200	500	1,500	2,500
CCF	2.75	1.54	1.00	0 92



Arrangement of Composite Material With Fibers Aligned at 0°, ± 45°, and 90°

- Turboprop (Propfan Powered Aircraft--Directs almost all of the gas turbine output to propellers. Utilizes new technology propeller blade airfoils and tip planforms and high solidity (eight blades) to reduce losses at high flight speed. Potential gain of 20% in fuel consumption over advanced turbofans at expense of initial power plant cost and maintenance and cabin noise and vibration. Potential direct operating cost savings of perhaps 5% although further study is required.

Range (statute miles)	500	1,500	2,500
Speculative CCF	1.46	0 95	0.87



Turbo Prop 100 1 Bypass Ratio | **Prop-Fan 50 1 Bypass Ratio**

Ground Transportation

- Improved Passenger Train (IPT)--Utilizes traditional twin steel rail, small improvements in existing guideways, advanced suspension systems and high power-to-weight propulsion; will permit speeds of 80 to 120 mph. Offers improved "block" (point-to-point) times with minimum investment.

Annual Trip Demand (millions)	5	40
CCF	2.21	2.14

- Advanced High-Speed Train--Requires new twin-rail high quality guideways with large radius curves, shallow grades, completely separated rights-of-way, together with advanced propulsion systems such as linear induction motors; speeds up to 250 mph design limit for rail; offers further improvement in "block" time at substantial guideway investment costs, about $3,200,00 per mile plus land and tunneling (or underpass) costs.

Annual Trip Demand (millions)	5	20	40
CCF	3.68	2.52	2.33

- High-Speed Ground Tracked Levitated Vehicles--Provide speed range from 250 to 600 mph System cost is dominated by guideway costs. Three noncontact suspension technologies are available. Costs are comparable.

  - Tracked Air Cushion Vehicle (TACV): fan or ram driven air is pushed through a large skirt (plenum) for suspension.

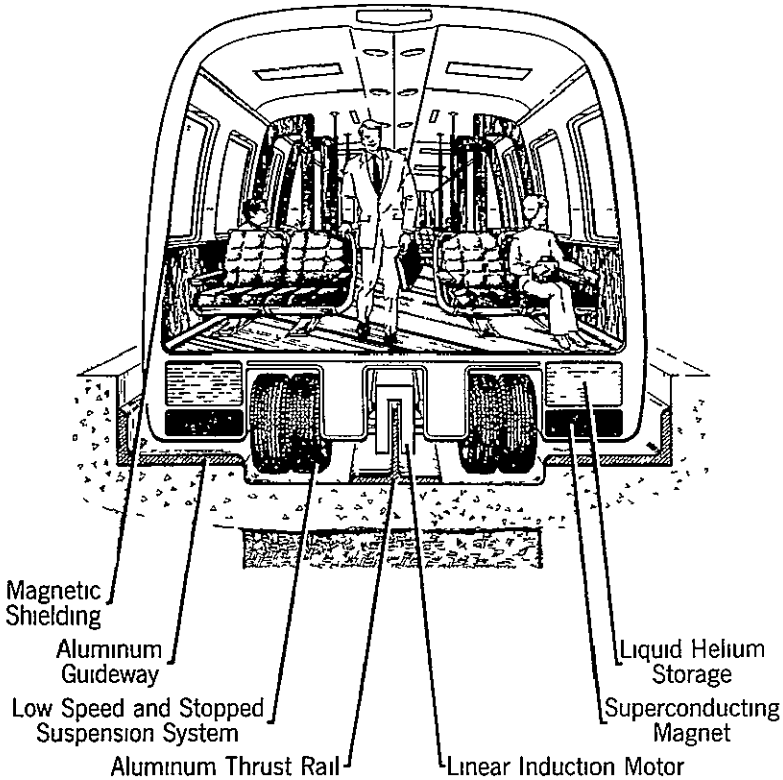
  - Magnetic Levitation (Repulsion) Motion of superconducting magnets over aluminum-lined guideway produces repelling magnetic field for suspension

  - Magnetic Levitation (Attraction)· Electromagnets attracted upward toward steel rails for suspension

  Propulsion options include linear induction motors, linear synchronous motors, or gas turbines (noisy)

  Fares become reasonable for short to medium ranges and very high demand Centercity travel times might be better than with aircraft.

Annual Trip Demand (millions)	10	20	30	40
CCF (all distances)	3.77	2.47	2.03	1.82



Stanford Research Institute MAGLEV Vehicle

- Bus--Public transportation using the highway system. Gas turbine propulsion may improve economy and passenger comfort. Requires minimum investment; flexible route capability Block speed = 50 mph under current speed limits.

  CCF 0 70

- Automobiles--The personally owned automobile will always be an intercity mode in the U.S. Privacy, convenience, and comfort are provided at a cost comparable to other modes, but at lower speeds than nonhighway modes. Improvements on engines, transmissions, and designs are expected to improve fuel economy by over 90% while maintaining acceptable emission standards. Automatic control of automobiles is technically feasible but probably not cost effective. Block speed = 50 mph, with current speed limits

  Perceived CCF (2.5 persons/car) 0.56

- Automated Highways--Various concepts to provide high-speed automatic control of automobiles or buses on highways. Based on radar or laser sensing of guiding stripe. Requires redundant control in the vehicle for safety. Significant cost impact. Current reduction of speed limits will reduce its potential value.

- Multimode Vehicles--Use of small, preferably electric, vehicles with local range but operable on an electrically powered guideway for intercity travel. Requires special guideway or special lanes on normal highway.

- Auto-Train Systems--Various schemes for transporting autos have been proposed including the Autotrain, now operating from Washington, D C. to Florida; proposals involving sled-like vehicles on a special electrically powered guideway (Roller-Road) and conveyor systems. Purely conceptual at this time

- Tube Concepts--Utilize deep tunnels, partially evacuated to reduce drag or even provide propulsion, require costly tunnel construction, may become of interest if tunneling technology is greatly advanced.

Direct Comparisons of Modal Characteristics

Block Time Comparison. The block times of the most probable air mode and the competitive ground modes are summarized in Figure II-1. These block times are based on departure from the vehicle "gate" and do not account for the passenger's access/egress time.

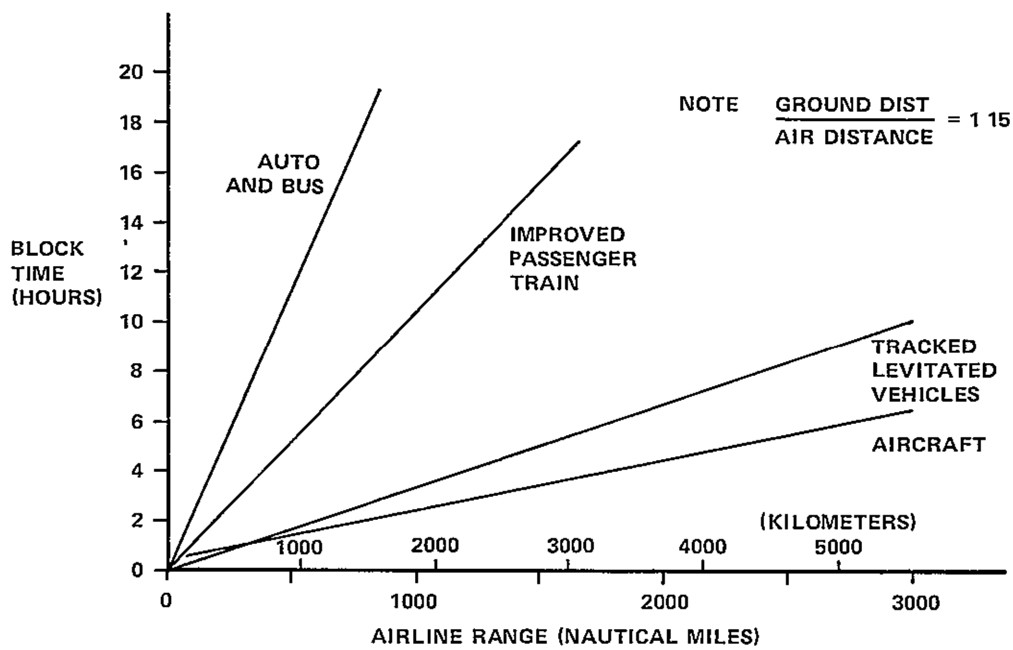


Figure II-1. COMPARATIVE BLOCK TIMES FOR VARIOUS TRANSPORTATION MODES

Energy Usage Comparison. A comparison of the energy consumption of various types of vehicles is shown in Figure II-2. Figure II-2 is constructed from energy consumption data given in the sections of this report dealing with the alternative modal technologies.

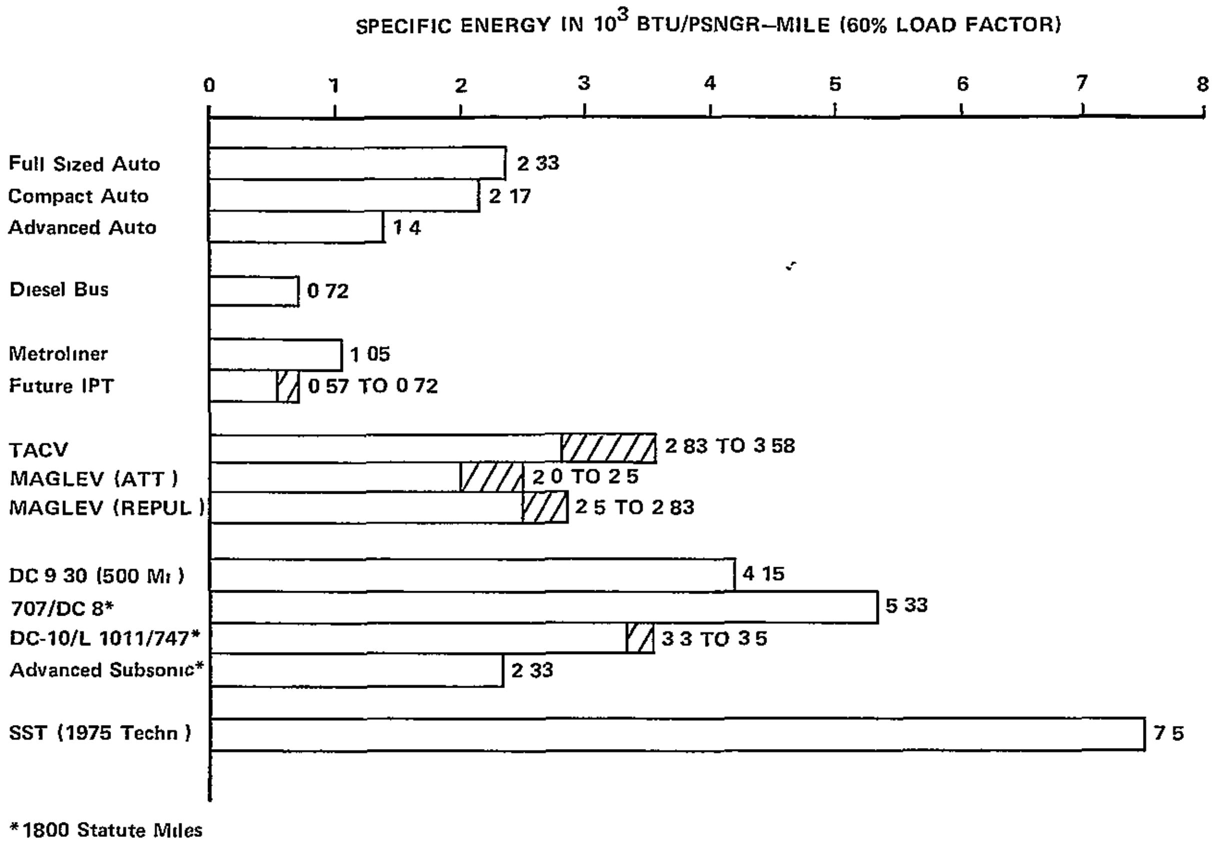


Figure II-2. COMPARATIVE ENERGY CONSUMPTION

Cost Comparison. An overall cost comparison of the major modes is shown in Figure II-3 as a function of range and passenger trip annual demand. The comparison is based on the fares required to cover the direct and indirect costs, amortization of the infrastructure investment, where this is not accounted for in either indirect costs or in a ticket tax as for air travel; and an 8% after tax profit on vehicle investment only. The class of distances and demands over which each mode is economically competitive is clearly shown. This graph and the block time curve on Figure II-1, summarize the economic and performance essentials of the various modes.

The fares in Figure II-3 are computed from the infrastructure and vehicle costs and the direct and indirect operating cost data, given in this report for the various modes.

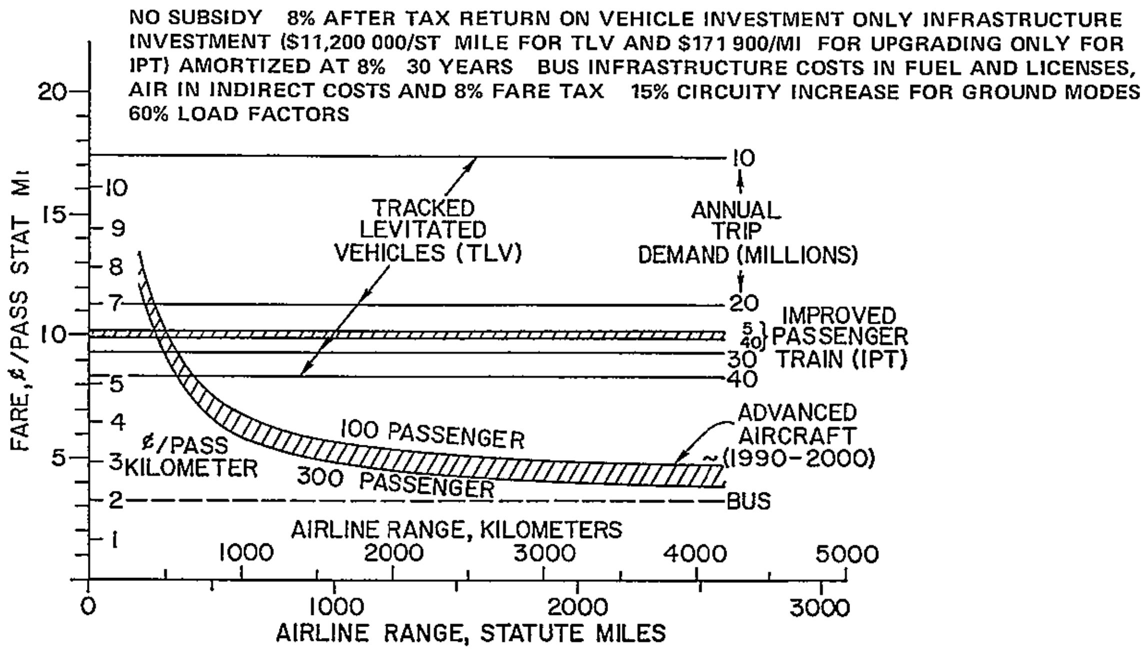


Figure II-3 COMPARATIVE FARES ($ 1974)
FOR VARIOUS TRANSPORTATION MODES

Mission Categories

Many transportation technologies are suitable for a wide range of missions and demand levels For example, improved materials and airfoils would be applicable to aircraft with capacities of 50 passengers or 1,000 passengers and ranges of 200 miles or 6,000 miles. On the other hand, because of the high power plant weight, nuclear propulsion is, as now foreseen, applicable only to very large aircraft, and because of its high cost can be justified only if a high value can be placed on essentially infinite range. Laminar flow control can save drag and fuel at all ranges, but the secondary savings due to reducing the airplace size as a result of lower fuel loads are much more significant at long ranges.

Similarly a MAGLEV system has such high initial cost that a high passenger demand is essential while buses can serve any density above a relatively small minimum. All ground systems compete best at short ranges and become less satisfactory as the range increases.

Although the categorization of the various transportation technologies must be less than rigorous, the most probable potential uses of each are indicated below.

International

Laminar flow control
Nuclear propulsion
Supersonic transports
Hypersonic transports
Hydrogen fueled aircraft
Advanced technology subsonic aircraft
(Improved airfoils, composite materials, active controls, etc.)
Turboprop powered aircraft

Long Range--Domestic

Laminar flow control
Supersonic transports (if sonic boom problem could be solved)
Hydrogen fueled aircraft
Advanced technology subsonic aircraft
Turboprop powered aircraft
Improved passenger train
Bus
Automobile

Medium Range

Laminar flow control
Hydrogen fueled aircraft
Advanced technology subsonic aircraft
Turboprop powered aircraft
Improved passenger train
Bus
Automobile

Short Range

Laminar flow control
Hydrogen fueled aircraft
Advanced technology subsonic aircraft
Turboprop powered aircraft
V/STOL aircraft
Improved passenger train
High-speed ground transportation (TACV, MAGLEV)
Bus
Automobile

III. TECHNOLOGICAL CHARACTERISTICS OF TRANSPORT AIRCRAFT SYSTEMS

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III. TECHNOLOGICAL CHARACTERISTICS OF TRANSPORT AIRCRAFT SYSTEMS

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Air Transportation

The development of air transportation has certainly been one of the most remarkable aspects of the last 50 years. In fact, the largest growth has occurred in the last 15 years since the entry into commercial service of the jet airplane offering large improvements in speed, comfort, and economics In attempting to evaluate what characteristics result in the successful introduction of new technologies in the transportation field, it is valuable to review the history of air transportation. Figures III-1, III-2, and III-3, taken from Reference 1, show the enormous growth in speed and airplane capacity of transport aircraft as well as the remarkable reduction in direct operating costs. The success of air travel has been linked to a constant improvement in service, primarily speed, range, and comfort, together with a large reduction in cost. Business, but especially in personal, travel is a somewhat dispensable commodity. Its use depends on whether the value gained from the trip is worth the cost Therefore, the economics must always be examined closely in judging the potentially successful implementation of

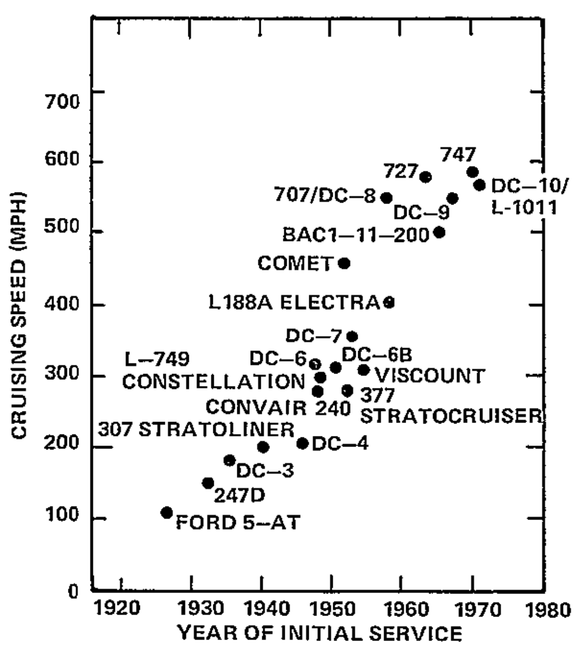

Figure III-1. SPEED HISTORY OF TRANSPORT AIRCRAFT

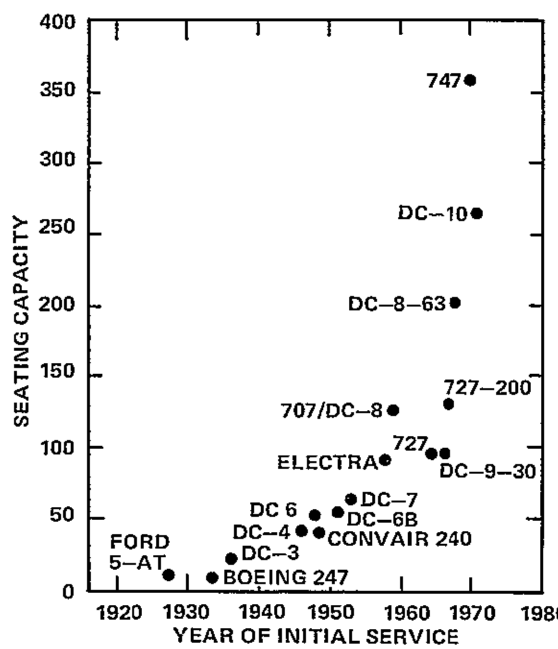

Figure III-2. GROWTH OF PASSENGER CAPACITY

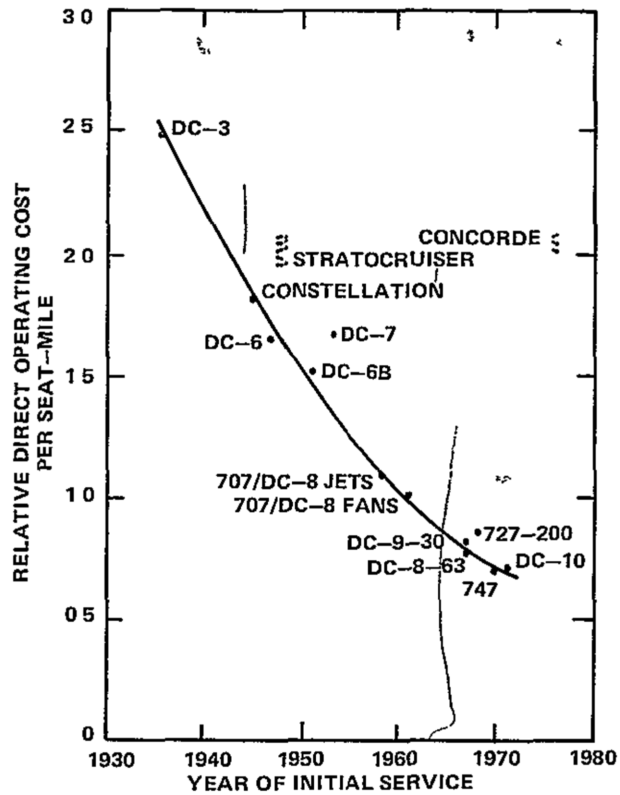

Figure III-3. DIRECT OPERATING COST
FROM THE DC-3 TO THE DC-10

an improved transportation mode. It is within this framework that new transportation modes must offer either improved service for equal or less cost, or improved service for a cost increase sufficiently moderate to be outweighed by the service advantage. It is not always easy to make this judgment; and therefore, in marginal cases we must assume that the new mode is a possibility. It is well to remember, however, that the enormous growth of air travel, as shown in previous figures, has always been associated with a cost decrease.

Following are the descriptions of the various technological developments that may impact on air transportation in the future.

Laminar Flow Control

Laminar flow boundary layers offer very large reductions in skin friction drag. Figure III-4 shows the comparison between the skin friction of the turbulent boundary layer, normally experienced in flight, and the

laminar boundary layer plotted against Reynolds number. At the Reynolds numbers typical of transport aircraft in cruise flight, between 20 million and 70 million, the potential reduction in skin friction approaches 90%. In addition, reducing skin friction diminishes the associated pressure drag. There is no other way to achieve such large drag savings. The pure turbulent skin friction of a typical airplane counts for 3/4 of the total parasite drag and about 45% of the total cruise drag. Elimination of, say, 70% of this skin friction drag, after allowing for the equivalent drag of the suction system power, can lead to overall drag reductions of 31% and an increase in the ratio of lift to drag of 45%. For a given mission, the large savings of fuel reduces the weight of the airplane and allows corresponding reductions in the size of the wing and tail because of the lower weight. Furthermore, with very low skin friction, the optimum airplane design is significantly changed It becomes profitable to use lower wing loading because of the reduced wing parasite drag and achieve significant reductions in induced drag that result from the larger span. Theoretically, the idealized design offers total improvements in lift/drag ratio on the order of 50%. This is partly counteracted by the weight of the additional wing area, associated with lower wing loading, by the higher construction weight of porous or slotted surfaces (Figure III-5), and by the weight of the pumping system required to draw away the boundary layer. Of course, in a practical design it would never be possible to achieve laminar flow over the entire aircraft, perhaps 80% of the wing and tail areas is a reasonable goal, but even this represents a reduction approaching 20% in parasite drag and a lift/drag ratio increase on the order of 18% including span effects. The exact values are dependent on the particular design since they are functions of the relative surface areas of the wing and fuselage Corresponding reductions in direct operating cost have been estimated at over 10%.[2]

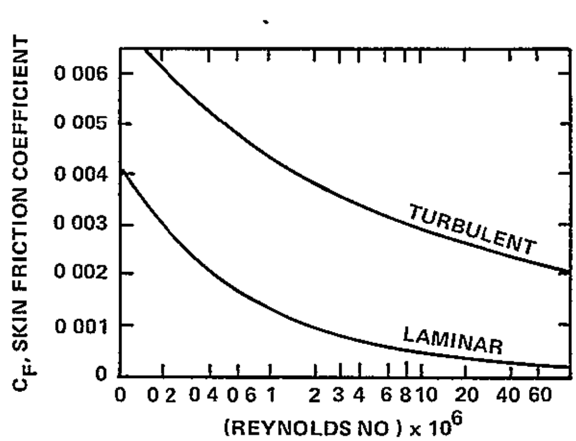

Figure III-4. LAMINAR AND TURBULENT (KÁRMÁN) SKIN FRICTION CURVES[3]

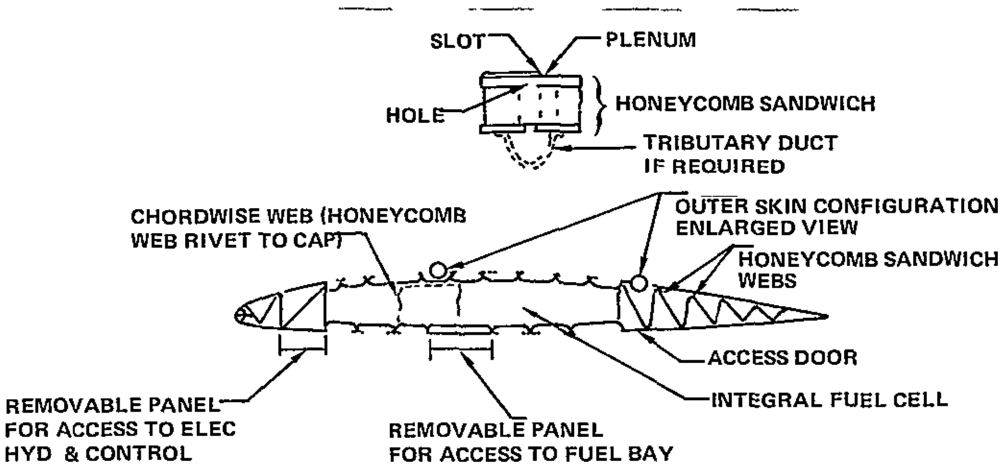

Figure III-5. SLOTTED SUCTION LAMINAR FLOW WING, NORTHROP X-21 AIRPLANE[4]

Since laminar flow control strives for significant reductions in drag, fuel consumption, and direct operating cost, it certainly offers desirable improvements The problem with laminar flow control has been the cost and difficulty in making wings with continuous suction capability, either through large numbers of holes or spanwise slots every few inches along the chord, as shown in Figure III-5, that were of sufficiently smooth quality so that the laminar flow could be maintained. Even in cases where this has been successfully achieved in occasional flight tests there is the continual concern about dirt or insects, the presence of which create sufficient roughness to change the laminar flow boundary layer to a turbulent one and destroy the possibility of achieving the expected drag gain.[5] There are associated maintenance problems with the suction system. Because of these difficulties, efforts toward laminar flow control have almost ceased.

Recent realization that the fossil fuel supply is limited and the sharp increase in fuel prices have stimulated reconsideration of laminar flow control. The development of new light porous materials made of woven graphite-epoxy fibers and the possibility of laser drilling of suction holes with a fineness previously unattainable might permit a cost-effective wing of sufficiently smooth quality to produce dependable laminar flow. Considerable research in the field is likely in the years ahead, but laminar flow control must still be considered to be highly speculative.

Nuclear Powered Aircraft

Nuclear powered aircraft were explored in considerable detail starting in the 1950s. Studies indicated that feasible nuclear aircraft would be possible with gross weights on the order of a million pounds.

Certainly most of those who worked on these studies, although aware of the handicaps of high shielding weight and certain radiation risks, felt that by 1970 nuclear aircraft would be flying. A major problem was the required weight of the reactor shielding to protect the crew and passengers

Today, 20 years later, it appears that a nuclear powered aircraft would require a takeoff weight of perhaps 1 5 million pounds to carry a practical payload.[6] This may not seem an insurmoutable obstacle since the 747 is already approaching 800,000 pounds gross weight However, the technological advances that would lead to greatly reduced nuclear shielding weights have not occurred and the development of flight weight reactors and heat transfer equipment have made only slow progress Because of the total power plant weight, Figure III-6, it seems that the payload carrying ability would be comparatively small even though the large fuel weight requirement of conventional turbine engines has been eliminated. The increased price of fossil fuels is certainly a favorable factor for the relative economics of the nuclear airplane. On the other hand, the costs of nuclear power plants and fuel, and the cost of the airframe to carry the heavy power plant, are such that even with high fossil fuel costs it is not at all clear that there would be an economic gain, or even a close equivalence On the basis of available data, the high investment costs appear to outweigh the fuel savings

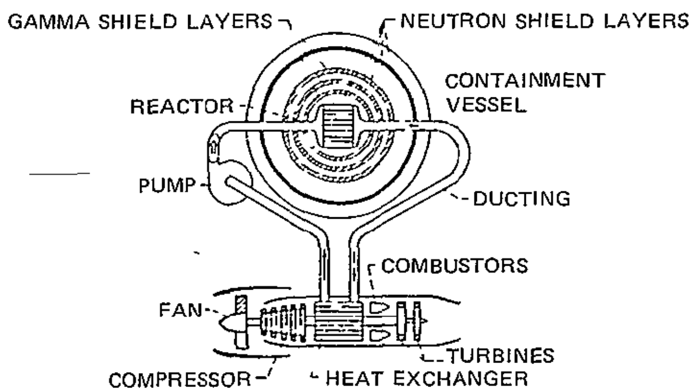

Figure III-6. SCHEMATIC DRAWING OF A NUCLEAR AIRCRAFT POWER PLANT (from Reference 6)

In addition, environmentalists are deeply worried about even stationary nuclear power plants protected by enclosures in which weight is no problem and located in relatively isolated areas. Obtaining the equivalent security with lighter weight shielding and encasement, and soothing

the concerns of carrying the nuclear plant in an airplane, which might crash in populated areas, seems to be an almost insurmountable task. The experts' words about feasibility sound very much like they did 20 years ago but the goals that would have to be met to overcome environmentalists' concerns are much greater. It is a safe guess that nuclear aircraft for commercial transport purposes are very definitely not on the near horizon and will not be seen in this century.

Short Takeoff and Landing (STOL) Aircraft

The development of short takeoff and landing (STOL) aircraft in short haul transportation is of a different nature than laminar flow control and nuclear aircraft in that the technology has been sufficiently developed to establish feasibility. True, there are still engineering and development aspects that have not yet been fully resolved but these uncertainties are matters of design optimization and the impacts on cost and reliability of complex control systems rather than fundamental questions of feasibility.

A STOL aircraft is generally understood to require a runway length of under 2,000 to 2,500 feet and utilizes propulsive lift The STOL issue has been much debated, often with less than complete objectivity. The fundamental problem with STOL arises from the fact that direct operating costs increase as design runway length is reduced. While true for any airplane, this trend is especially marked below 3,000 feet. Furthermore, on a high density route the required increase in fare, Figure III-7, is large compared to the prorated amortization cost of another 1,000 feet or 2,000 feet of runway length.[7,8] It is often argued that only a 2,000-foot runway or less can be located close to city centers. There are few places, however, that can accommodate a 2,000-foot runway, but not a 3,000-or-3,500-foot runway. Equally important is the fact that environmental considerations such as noise, safety, and congestion will probably prevent any significant number of city-center STOLports anyway.

Another difficulty facing high density commercial STOL is fuel consumption. The fuel requirement for a 150-passenger aircraft at a 350 statute mile range is shown in Figure III-8 as a function of required field length. The 2,000-foot runway case uses 35% more fuel than the 3,000-foot design and 45% more than the 4,000-foot design. The increasing value of fuel conservation as a virtue in itself will further impede the development of STOL aircraft.

We conclude that STOL aircraft will be limited to possible military purposes and to small aircraft responsive to very specialized needs. STOL aircraft cannot be expected to make a significant impact on air transportation

What we can expect in the short-haul market is the development of much quieter aircraft, with field lengths somewhat shorter than at present,

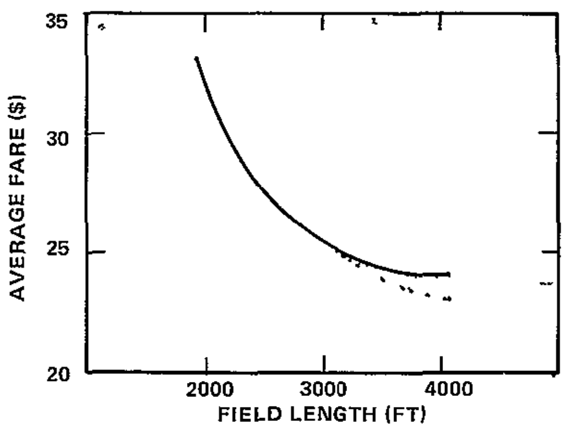

Figure III-7 FARE VS. DESIGN FIELD LENGTH IN THE CALIFORNIA CORRIDOR FOR QUIET PROPULSIVE LIFT AIRCRAFT (1972 DOLLARS)[8]

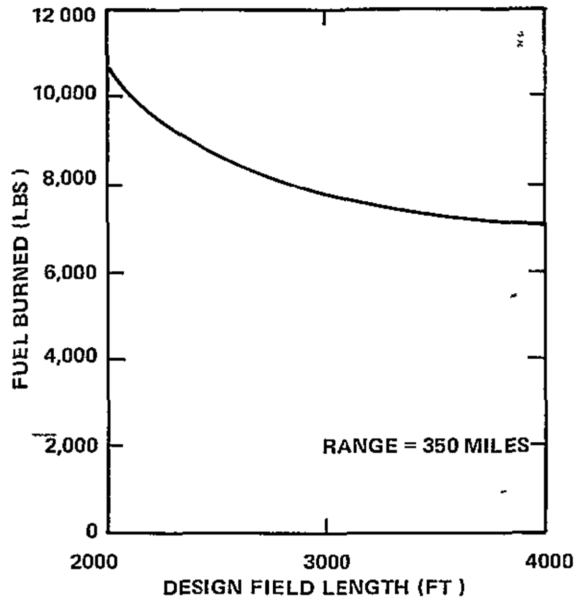

Figure III-8. FUEL BURNED VS. DESIGN FIELD LENGTH[8]

separated as much as possible from the long-haul system primarily through the use of existing general aviation fields. These aircraft may benefit from some use of propulsive lift even though the field lengths may be 3,500 feet to 4,500 feet.

Vertical Takeoff and Landing (VTOL) Aircraft

Extrapolating STOL performance to zero field length leads to vertical takeoff and landing aircraft (VTOL) VTOL aircraft are the most expensive in terms of productivity per unit cost. For this reason, helicopters, the only operational VTOLs except for the Harrier fighter, have had and will continue to have little impact on commercial air transportation. Helicopters offer an ability to operate from sites that no other aircraft, and sometimes no other vehicle of any type, can handle. Therefore, helicopters will have a large continuing role in military missions and industrial service such as supplying offshore oil drilling installations Although helicopter efficiency can be expected to improve in the decades ahead, there are no technical developments known to this author that will remedy the relatively poor economics.

Various new types of vertical takeoff and landing aircraft are under development. The most significant are lift fan vehicles in which

tip-driven fans in bodies or wings provide vertical lift, lift-cruise fans in which fans, possibly tip driven, provide both thrust at cruise and lift at takeoff or landing with the direction of the thrust being controlled by adjustable ducts; and tilt-rotor aircraft with rotors that can be positioned to provide vertical thrust for takeoff or tilted forward to product forward thrust when the speeds are high enough to obtain the lift from wings. The latter is probably the most promising, but tilt rotor costs and technical problems are not yet established Considerable improvement over helicopter economics due to higher cruise speeds can be anticipated.

Supersonic Transports

The most intense effort of the last decade in aircraft technology has been the supersonic transport, Figure III-9. In the United States, supersonic transports were first predicted to have a viable future in the late 1950s. About the same time, several aircraft companies and the National Aeronautics and Space Administration began intensive configuration studies and development efforts. The project was buffeted by alternating waves of optimism and pessimism with respect to obtainable ratios of payload to gross weight and lift to drag and the anticipated economics

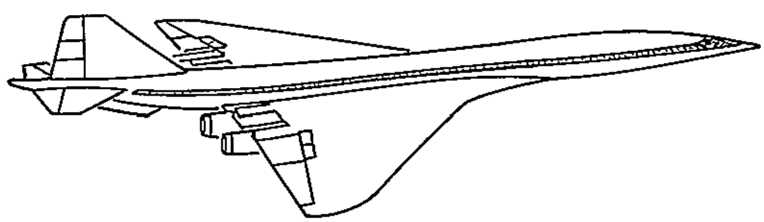

Figure III-9 BOEING 2707 SUPERSONIC TRANSPORT

The development process of the supersonic transport represented a fundamental departure from previous commercial aircraft. The capital investment required for development, flight test, and production tooling was so large that no single aircraft company, or even a consortium, could afford to undertake the project. In the United States, therefore, the government undertook a program whereby 90% of the development funding was to come from the government and the remaining 10% from private industry. The government's investment was to be eventually returned from the proceeds of the sale of the aircraft. Very large markets, projected as high as 500 aircraft, were anticipated. In Europe, the

British and French governments joined earlier to develop the Concorde with the same expectation of recovering the investment from the sale of the aircraft.

In 1975, we find the United States supersonic transport program non-existent, having been cancelled in 1971, and the Concorde program suffering from severe doubts about its economic wisdom. The U.S. supersonic transport candidate, the Boeing 2707, died from such a complex illness that even today the primary cause is not clear. Some people remember the environmental problem as the prime objection, particularly the concern over reduction in the ambient ozone concentration at high altitudes, others think the SST was the victim of a dramatic reordering of national priorities that coincidentally occurred about that time, while still others feel that its economic disadvantages were the major cause

A strong case can be made for the point of view that the dubious economics of the project was a prime reason for its demise. In 1969, the Boeing 2707 had an estimated direct operating cost almost 50% higher per seat-mile than that of the 747 as shown in Figure III-10 taken from Reference 9. Block time advantages are shown in Figure III-11 In terms of the functional characteristics we have observed in past airplanes, the 2707 had a very great speed advantage, indeed a cruise speed slightly over three times as high as current subsonic aircraft, a small decrease in comfort resulting from the supersonic drag requirement for a narrow body, and an increase in direct operating cost much higher than any transport aircraft had ever been able to tolerate We are faced with the very difficult problem of trying to determine whether or not our basic figure of merit, the service/cost index is improved. Neglecting the small decrease in comfort, since the shorter flight times would more than compensate for this, it is simply a question of how much more the passenger will pay to save a given amount of time. Analysis of the problem hinges primarily on the question of the value of time. Also affecting SST economics was the total market and its relation to the sonic boom. Since the sonic boom over land was a serious environmental problem, the market for the aircraft was substantially decreased.

The critical economic issue is the value of time for air travelers and, for many business travelers, the value placed on their time by their employers. In some recent SST economic studies, the value of time has been taken to be twice a man's earning rate per hour for business travel and 1-1/2 times his earnings rate for personal travel. Serious questions can be raised as to how many travelers would pay that much premium. Much more reasonable values of time might be the actual earning rate for business travel and one half the earning rate for personal travel

The enormous increase in fuel price in recent years would substantially increase the cost difference between the SST and the 747. The original 50% higher direct operating cost the SST suffered with respect to the 747 would increase to about 70% higher cost with double fuel prices and

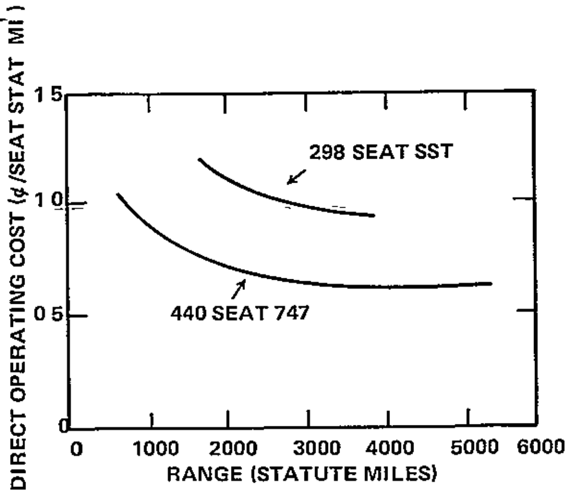

Figure III-10. COMPARISON OF DIRECT OPERATING COSTS FOR THE BOEING SST AND 747 AIRPLANES [9]

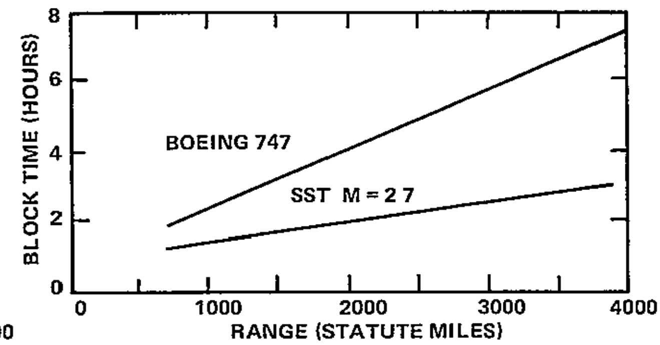

Figure III-11. COMPARISON OF BLOCK TIMES FOR THE BOEING SST AND 747 AIRPLANES

85% higher cost with triple fuel prices, the latter being typical of current international fuel costs.

Of course, the fare does not rise linearly with direct operating cost. Roughly half of current total cost is indirect cost Since indirect costs include cabin service and flight attendants' salaries, the high speed of the SST would slightly reduce the indirect cost per seat-mile. On the other hand, the fare required for a given return on investment is not simply a constant times the total operating cost. The nature of the fare is shown by the following equation for a specified discounted-cash-flow rate of return:

$$\text{Fare/pass./trip} = \frac{T_B \cdot A \cdot IC}{U \cdot lf \cdot N} + \frac{DOC \cdot d}{lf} + \frac{IOC \cdot d}{lf}$$

where

T_B = flight block time (hours)

A = constant, dependent upon rate of return on investment (ROI) and depreciation period

IC = total initial cost of the aircraft including spares ($ per unit)

U = aircraft annual utilization (hours per year)

lf = load factor, the ratio of passengers to available seats

N = number of available seats per aircraft

DOC = direct operating cost

d = air distance, statute miles

IOC = indirect operating cost

This equation assumes that each segment has a fare that provides the desired return on investment. For a 12-year depreciation period to zero residual value, the value of A is 0.1503 for a rate of return of 12%, after U.S. taxes, and 0.0948 for an ROI of 8%.

The first term is the portion of the fare required for profit. The percentage of the total fare involved in this profit term varies with airplane type and the return on investment and is 12% to 35% for an ROI of 12%. Assuming a load factor and a required rate of return on investment, say 12%, the fundamental parameters in comparing one airplane with another are the relative block time required per flight and the cost per seat. In the case of a projected second generation SST with a cruise Mach number of 2.7, the block time on a transatlantic flight would be about 45% of the subsonic jet time. Based on current estimates, it appears that the cost per seat, in 1972 dollars, would be about \$250,000 to \$280,000 compared to a comparable value for the subsonics of approximately \$70,000 per seat The product of the block time ratio times initial cost per seat ratio leads to a higher dollar value of the profit term by about 60% Thus the profit term, which is on the order of 15% of the total fare, will suffer a percentage increase that is larger than the increase in the direct operating cost based on 1972 fuel prices. As a result it would appear that the Boeing 2707, if it had been built and in the framework of 1972 dollars and fuel costs, would have required a fare about 31% higher than the widebody subsonics. The tripling of fuel prices would have raised this value to more than a 45% increase in fare. With transatlantic coach fares being \$290 to \$380 from New York to London, depending upon the season, the pertinent question is then whether passengers would be willing to spend an additional \$130 to \$170 to save 3.5 hours. We might guess that almost all first class passengers would--since they already pay that level of fare--while very few coach passengers would use the SST.

The Concorde, a fantastic technical achievement, has a considerably higher direct operating cost per seat-mile than the projected Boeing 2707, an investment cost per seat on the order of \$370,000 and a lesser block time advantage than the projected Boeing SST. Concorde direct operating costs are three times the current subsonic costs based on 1974 fuel prices, Figure III-3, and total operating costs are about twice the subsonic level Although there are certain people who will

pay over $100 to save an hour of time, it would appear that this is a very small part of the market. Such fares cannot attract sufficient numbers of passengers to make a significant impact on air transportation. Recent studies of advanced supersonic transport technology indicates that the time has not yet come when we can foresee a supersonic transport that can show a fare within 10% to 20% of existing aircraft. Many people believe that such fares will have to be achievable before we can have a viable unsubsidized supersonic transport.

Environmental requirements bear heavily on the SST. The problem of ozone depletion at SST cruise altitudes due to interactions with the nitrogen oxide present in jet engine exhaust has been shown to be significant This particular issue demands and is getting attention. It may be possible to develop engines with sufficiently low nitrogen oxide concentration in the exhaust to alleviate this concern. The problem of meeting current noise standards without imposing heavy economic burdens on the aircraft is still unresolved.

A new major concern is fuel consumption. Based on current data, the fuel required per passenger-mile by advanced SST aircraft would be more than twice that of the subsonic widebody jets as shown in Figure III-12. The Concorde fuel consumption is about three times as great as the subsonics. The effect of this shows up in direct operating cost, of course, but beyond the actual fuel cost is the development of a conservation ethic. The question may well arise whether government funds should be used to foster a commercial project which will be used by only a small percent of the population and will consume two to three times as much fuel per passenger mile as existing air transportation. Certainly in the United States and Europe, it is easy to foresee powerful political objections to the initiation of such a project.

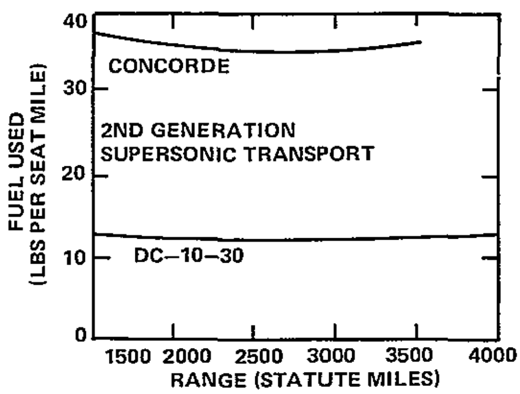

Figure III-12. COMPARISON OF SUBSONIC AND SUPERSONIC TRANSPORT FUEL CONSUMPTION

In any case the very difficult sonic boom problem would have to be resolved to permit domestic use of the SST. In addition, the dubious economics rapidly deteriorate at shorter ranges so that below about 1,500 miles even a viable SST would probably not be attractive in relation to its subsonic competitors.

The SST, being so marginal at present, can be considered as a highly leveraged product. Significant gains in aerodynamic, propulsive, or structural efficiency could greatly increase the payload, with a correspondingly large decrease in direct operating cost. History has shown that such major steps are usually led by engine developments. Therefore, a technological breakthrough may someday make the SST an economically viable form of air transportation. At that time government development financing becomes reasonable. The technological advances can only occur if research is continued at a reasonable rate in propulsion, aerodynamics, and structures The propulsion effort must focus not only on efficiency but also on the environmental problems of noise and nitrogen oxides.

Hypersonic Transport (HST)

The hypersonic transport (HST) represents an even larger technological step forward from SST technology than SST technology from current subsonic jet technology The development costs and technological risks are of astronomical proportions. The most optimistic analysis would not predict the advent of a commercially feasible HST before the end of the century.

HST faces severe technological, economic, and environmental problems Technologically, an HST requires significant advances in propulsion, structures, and aerodynamics. A dual-mode propulsion system is required turbojets for subsonic and low supersonic speeds and ramjets or scramjets (supersonic combustion ramjets) for hypersonic cruise. Such a dual system introduces the need for complex separate controls, as well as variable inlet and nozzle geometry and doors to close the inoperative engines. Because of the extreme engine temperatures, an engine cooling system would be required, with cryogenic liquid hydrogen appearing to be the best heat sink available. The hydrogen coolant would then flow to the engine combustion chamber and serve as the fuel. The logistics of hydrogen fuel is an enormous and complicated problem in itself.

The structural design problems of an HST are as formidable, if not more so, than those of the propulsion system. Most notable is the fact that the stagnation temperature of a Mach 6 HST at 100,000 feet would be 2000°F.[10] Such temperatures would require either the use of high-temperature materials or normal aircraft materials coupled with a thermal protection system. Three candidate thermal protection schemes are active cooling, insulation, and radiation shields[11] or combinations of the three Large temperature gradients through the aircraft

represent additional structural complications, not to mention containment and insulation of the cryogenic hydrogen fuel. Any solution to these problems must be economically reasonable, demanding low manufacturing cost, long life, and low maintenance.

Aerodynamic considerations, though less severe than propulsive and structural problems, demand significant state-of-the-art improvements. For example, static longitudinal stability variations with increasing Mach number would require a sophisticated fuel management system to avoid excessive trim drag. Directional stability is also a problem which is aggravated at higher Mach numbers.

In summary, the technological advances required before an HST is technically feasible, let alone economically plausible, are significant.

Economic performance of an HST is highly speculative although a recent study[11] indicates marginal economic viability. Development and production of an HST would require an extremely large capital investment: ~\$6.2 billion.[11] Such an investment is beyond the means of most national governments, let alone private enterprise. The development of HST, then, would probably require an international cooperative effort.

HST economics are largely dependent on design range and fuel cost. Assuming a million pound gross weight Mach 6 vehicle and 10 cents/pound LH_2 cost (optimistic), DOC varies between 1.5 and 2.5 cents/seat-nautical-mile for design ranges between 3,500 and 5,500 nautical miles. A fuel price of 15 cents/pound (conservative) would produce a DOC of ~3 cents/seat-nautical-mile.[11]

The environmental problems associated with an HST are probably more severe than those of an SST. One of the more important problems is the projection that a fleet of HSTs would produce water vapor in the atmosphere at a rate comparable to what occurs naturally. The resulting climatic impacts could be significant. Likewise, the effect of nitrogen oxide emissions are serious and may be more difficult to control in hypersonic ramjets than in turbojets.

Like SST, HST would present a sonic boom problem This would be most acute during climb and acceleration; during cruise the overpressure is predicted to be less than 1 psf.

Lighter-Than-Air

Lighter-than-air (LTA) vehicles have received considerable publicity in recent years. A reasonable estimate of the economics of dirigibles can be made quite simply. A brief unpublished study by the author of a dirigible the size of the Macon, with a displacement volume of 7,400,000 cubic feet, would indicate that the direct operating cost of a cargo-carrying dirigible would be four to five times that of a 747 at 1/6th the speed. This study was based on assuming the same crew cost as a

747, although the crew would obviously be on duty for very long periods of time (or at least they would be trapped aboard the vehicle without salary when they weren't on duty); first cost and airframe maintenance cost comparable to the 747; 25% higher hourly utilization for the dirigible; sharply reduced maintenance cost on the engines, and only 5% of the fuel cost This study also assumed a 20% structural weight savings due to technology. Due to the low flight altitude of these vehicles, their difficulty of handling, the large land areas required to store them on the ground, the slow speed and direct operating costs enormously higher than present aircraft, they have no transportation future. A remote possibility that such vehicles might serve a purpose for special lifting jobs may exist, but this really is not part of what we would call the transportation system.

It has recently been suggested that LTA vehicles may have a role in very short-range passenger transport such as feeding major airports. The preliminary studies indicate that only 20% of the lift should be static, which is getting close to no buoyancy at all.

Hydrogen-Fueled Aircraft

A fertile field of study for future transport aircraft is the use of alternative fuels. Liquid hydrogen is the most spectacular of these possibilities. Liquid hydrogen benefits first from its high energy content per pound. As shown in Table III-1 from Reference 12, hydrogen has 51,590 Btu per pound compared to 18,400 Btu per pound of kerosene, a ratio of 2 8. Since weight is so important in aircraft design, there is an enormous advantage in reducing the weight of fuel required. The disadvantage of hydrogen is its low density. Since a pound of liquid hydrogen fills 10.6 times as much volume as a pound of kerosene, the overall result is that for a given amount of energy, hydrogen requires a volume that is 3.8 times as large as kerosene.

The result of these characteristics is that a hydrogen-powered aircraft looks quite different from a conventional jet-fuel-powered aircraft. The differences are in the use of a very large fuselage to carry the additional fuel or, alternatively, in the presence of very large bodies placed on the wings to provide the extra tankage. This increased volume increases structural weight and drag. On the other hand, the much lighter quantity of fuel required greatly reduces the takeoff weight and permits smaller wings and engines.

Studies by Lockheed[12] and Douglas[13] have indicated that subsonic hydrogen-powered aircraft, designed for ranges of 3,400 to 5,000 miles respectively, would have a takeoff weight reduction of 26% to 34% and an engine size reduction of 0% to 30%, but a weight empty reduction of only 7% to 10%. The reason for the small reduction in weight empty is that the reductions in structural weight due to the lighter takeoff weight and smaller engines are largely balanced by the larger structural weight required to house the high volume of fuel. Because of the large

Table III-1

PROPERTIES OF SOME CANDIDATE FUELS

	JP Fuel	Methane	Ethyl Alcohol	Methyl Alcohol	Ammonia	Hydrogen
Nominal Composition	$CH_{1.94}$	CH_4	C_2H_5OH	CH_3OH	NH_3	H_2
Molecular Weight	≃120	16.04	46.06	32.04	17.03	2 016
Heat of Combustion (Btu/pound)	18,400	21,120	12,800	8,600	8,000	51,590
Liquid Density (lb/ft^3 at 50°F)	47	26.5[a]	51	49.7	42.6[a]	4.43[a]
Boiling Point (°F at 1 atmosphere)	400 to 550	-258	174	148	-28	-423
Freezing Point (°F)	-58	-296	-175	-144	-108	-434
Specific Heat (Btu/lb °F)	0.48	0.822	0.618	0.61	1.047	2.22
Heat of Vaporization (Btu/pound)	105 to 110	250	367	474	589	193

a. At boiling point.

reduction in average flying weight, even though there is somewhat more drag due to the large fuel storage requirements, the fuel energy requirement is down approximately 5% to 20% and the fuel weight by a very large 65% to 70%.

The economics of hydrogen aircraft is a different story. Hydrogen is expensive to produce and expensive to liquify. Figure III-13, reproduced from Reference 14, shows the estimated production cost, in 1973 dollars, of liquid hydrogen produced by various methods. Also shown are costs of kerosene and liquid methane. It will be seen that hydrogen is very much more expensive than kerosene to produce per unit of energy.

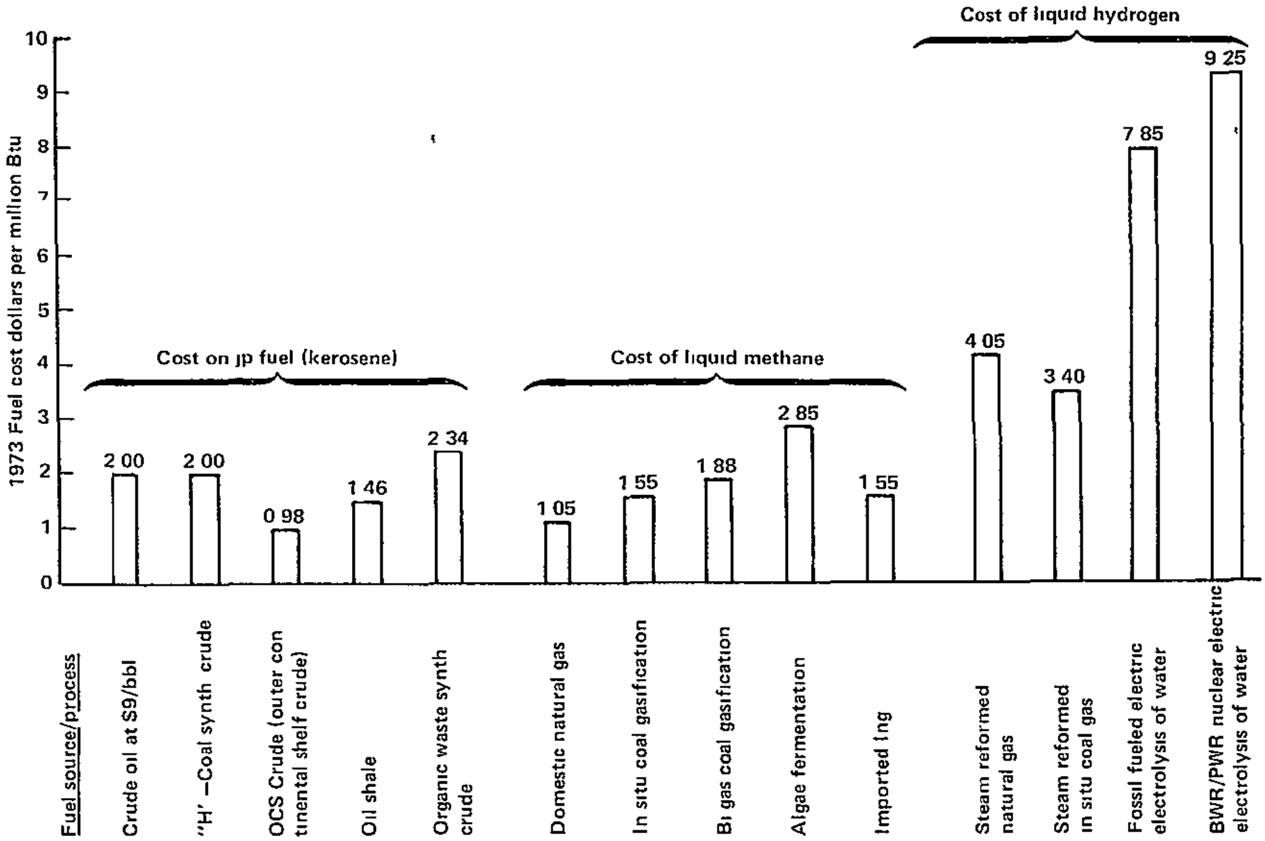

Figure III-13 COST COMPARISON OF UNITED STATES ALTERNATIVE TRANSPORTATION FUELS (1973 DOLLARS)

It is often said that we have a limitless supply of hydrogen in the oceans but, it will be noted, that the electrolysis of water to produce hydrogen results in cost 4 to 4-1/2 times as high as conventional jet fuel. The least expensive means of producing hydrogen from natural gas or coal gas still shows costs twice as high as kerosene. It is for this reason that studies performed on hydrogen aircraft do not show improved economics, although using the least expensive estimates of the cost of hydrogen can result in direct operating costs that are only of the order of 10% higher than conventional aircraft.[15] Another important problem with production of hydrogen from water is that the electrolysis process used requires 4 2 to 4.9 Btu of heat energy to produce 1 Btu of liquid hydrogen Unless the 4.2 Btu can come from some unlimited source of power such as fusion or solar sources, this does not appear to be the way to conserve energy resources.

Another problem with hydrogen is that an entirely new logistic system for the transportation, storage, and handling of fuel would be required at airports throughout the world. The investment would be extremely high and these costs are probably not reflected in the studies that have been done on the economics of hydrogen Figure III-13 shows another

interesting aspect of the fuel problem. It suggests that one can produce synthetic kerosene from coal much cheaper than one can produce hydrogen. Since coal is our largest natural resource, it would seem much more efficient to produce the fuel we are accustomed to using, which leads to lower airplane operating costs, and does not require a total revision of the fuel supply system, than to produce hydrogen from coal with no economic or energy source advantage. The one advantage that would accrue from hydrogen is that it is a nonpolluting fuel. However, the pollution effects of aircraft are limited to the immediate vicinity of the airport, and with the improved engine design and operational methods, a great deal of the objectionable kerosene smell from ground operations should be capable of being substantially reduced.

Because of the high cost and the major revision of the supply and logistic system required for the use of hydrogen, it is not believed that hydrogen aircraft will play any role in commercial aviation through the year 2000. Based on the ability to produce kerosene at less cost from coal than hydrogen can be produced from the same source and the lack of any economic advantage due to the hydrogen, it seems unlikely that hydrogen is significant in the future of commercial aviation--until cheap unlimited energy becomes available from fusion and solar sources. A much less expensive and less energy consuming method of producing hydrogen from water, and liquifying it, is required before this conclusion can be changed

Improved Transonic Airfoils

The improved transonic or supercritical airfoil was originally developed by Dr. Richard T. Whitcomb of the NASA Langley Research Center. It appears to be one of the few developments for which all aspects are favorable Usually every advance brings its problems For example, sweepback permitted increased speed but increased structural weight and adversely affected maximum lift coefficient. It appears that these airfoils, which are being pursued in many countries in universities, industry, and national laboratories, can offer a substantially higher Mach number for initial drag divergence, M_{DIV}, for a given airfoil thickness, an excellent structural shape, and high maximum lift coefficient.

Figure III-14 shows the difference between the pressure distribution of one of the new transonic airfoils and the type of peaky pressure distribution airfoil currently in use on most modern transports. The main characteristic of the new airfoils is an increase in the loading toward the rear of the airfoil due to aft camber. Carrying this aft load makes possible a reduction in the pressure coefficient, C_p, at and aft of the airfoil crest. The crest is the point on the upper surface tangent to the freestream. Lowering the negative pressure coefficient at and aft of the crest raises the drag divergence Mach number.

Another characteristic of the airfoil is the very flat upper surface which serves to greatly reduce the vertical projection of the aft

facing surface until a point far back on the airfoil. Thus, even after the local speed of sound is exceeded at the crest and high suctions are produced well back on the airfoil, the sharp drag rise caused by having large suctions on the aft facing surface behind the crestline of conventional airfoils is postponed by a few hundredths of a Mach number.

The third characteristic of the transonic airfoil is the tangency of the upper and lower surface which eliminates the large pressure increase normally found at the trailing edge of an airfoil and permits the higher adverse pressure gradient required by the aft loading, without causing separation on the upper surface of the wing. The relatively flat surfaces permit greater structural depth of the front and rear spars for a given overall airfoil thickness. The only disadvantage of the airfoil is the difficulty of constructing a section with a tangent upper and lower surface of the trailing edge This requires a very thin section. It appears, however, that modern structural technology can handle this problem with honeycomb techniques.

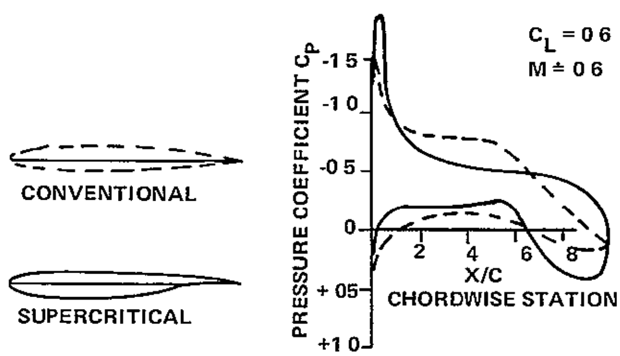

Figure III-14 ADVANCED TRANSONIC (SUPER-CRITICAL) AND EXISTING TRANSPORT AIRFOIL PRESSURE DISTRIBUTIONS

There are various ways that one can use the transonic airfoil. First, the cruise Mach number can be increased by 0.07 to 0 08 Mach number for a given wing sweep and thickness, Figure III-15. This increased speed without structural weight penalty actually improves direct operating cost since direct operating cost varies almost inversely as block speed. Furthermore, the fuel burned is nearly the same. Increasing the speed improves the value of miles flown per pound of fuel. The increase in specific fuel consumption with speed, characteristic of high bypass ratio engines, and the higher engine weight required at the higher cruise Mach number approximately cancel the fuel gain. The

overall result can be to improve cruise speeds from, say, 0.85 to 0.92 with no fuel penalty and a direct operating cost gain of several percent.

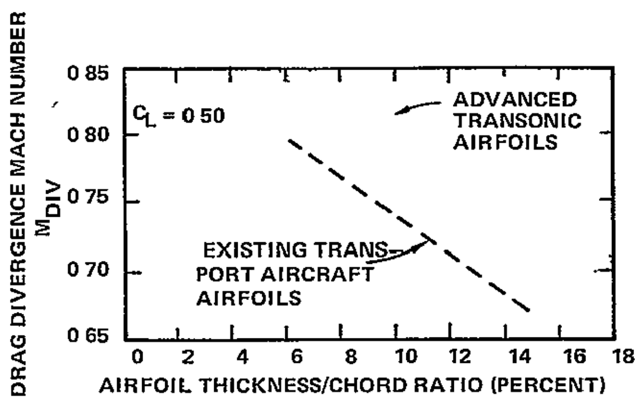

Figure III-15. ADVANCED TRANSONIC (SUPERCRITICAL) AIRFOIL PERFORMANCE

Another way to utilize the improved transonic airfoils is to maintain current cruise speeds and either use less wing sweep which increases the maximum lift coefficient and, for a given aerodynamic aspect ratio, decreases the wing weight or increase wing thickness ratio which significantly reduces wing weight. The latter, however, may increase airfoil profile drag sufficiently to negate much of the potential fuel savings. In practice, combinations of thickness increase and wing sweep reduction would be studied to find the optimum configuration for any design speed. Significant benefits can be obtained if the design cruise speed is high enough to require thin wings, below about 12%, and/or sweepback angles above about 20° with current airfoils. A typical current aircraft cruising at M = 0.85 could benefit by about 4% in direct operating cost and 5% in fuel requirements In addition, the reductions in weight and the increases in thickness permit the use of higher aspect ratios with less weight penalty than heretofore. The higher aspect ratio raises the lift-drag ratio and further reduces fuel consumption. The further reduction in fuel may be about 10%.

Active Control Technology

A major technological effort has been concerned with the use of rapid response automatic control systems to provide static and dynamic stability, thereby permitting reductions in tail surface area, to limit loads generated by gusts and even to control flutter. Reducing gust loads would extend fatigue life and even permit designing the structure to lower maximum loads. Using control action to prevent flutter would

eliminate weight increases sometimes required to increase wing stiffness above that provided by a structure designed for strength. Cost and fuel savings would result from less drag with small tail surfaces and less structural weight because of reliance on load and fatigue limiting by control systems

Fundamentally, the concept replaces some tail area and structural material with "black boxes." Multiple fail-operative redundancy would be required. The high acquisition and maintenance cost of the equipment will have to be balanced against weight and drag savings. The net gain is not yet clear and the impact on transport aircraft will be small for some years. Nevertheless, automatic control when properly developed and backed up by sufficient redundancy has been demonstrating high reliability The first use of active controls will probably be to permit reduced static stability but only to a level which is not unsafe but merely uncomfortable to the crew Then the rare chance of failure will require increased pilot attention without introducing a hazard. Reduced static stability will permit smaller tail areas, therefore saving tail surface weight and drag and trim drag The associated reduction in direct operating cost has been estimated at 2% to 4%, with an associated fuel savings of 4%

Advanced Filamentary Composite Materials

Another major technological development of recent years is advanced composite materials for structure.[16,17] These materials, composed of graphite or boron fibers in an epoxy binder or matrix, offer very superior ratios of strength and stiffness to density. Figure III-16 shows a comparison of aluminum, steel, titanium, and graphite-epoxy composite material in terms of specific tensile strength and specific tensile modulus. The improvement over the conventional alumunum alloys is about 50%, offering very large reductions in structural weight Composite materials do have difficulties, however Since composites are not isotropic or homogeneous and lack the ductility of metals, the usual fittings and bolt and rivet fasteners cannot be used A long development has been necessary to develop an understanding of the material and to learn to construct it with fibers running in various directions in order to optimize the strength and stiffness for the specific applications, Figure III-17. Now it appears that many of these problems are being overcome. Another difficulty has been the very high cost of material and fabrication With increasing use of composites, however, material costs, particularly for the graphite-epoxy composite, are dropping sharply. Furthermore, fabricators are learning how to handle the material efficiently Many people working with composites now feel that the fabrication costs will eventually be lower than the fabrication costs of aluminum. As a result, there is reason to hope that use of composite materials will yield both weight and cost savings.

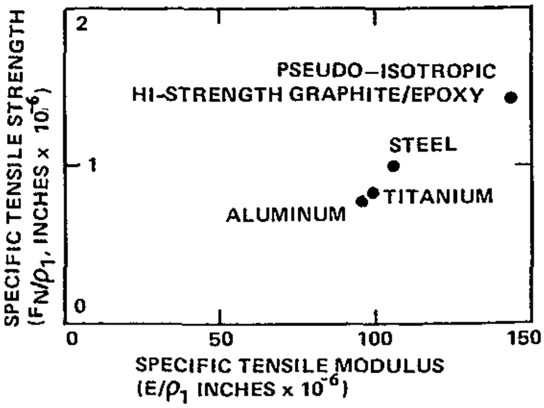

Figure III-16. COMPOSITE MATERIAL SPECIFIC STRENGTH AND MODULUS COMPARISON (FROM REFERENCE 18)

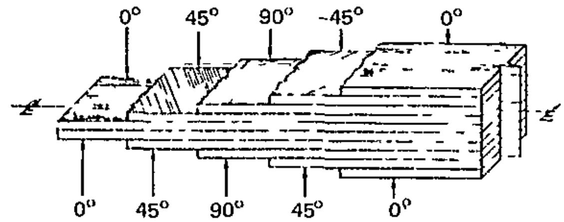

Figure III-17. ARRANGEMENT OF COMPOSITE MATERIAL WITH FIBERS ALIGNED AT 0°, ±45°, AND 90°

A third disadvantage of composite materials is lack of experience Aluminum structures have been used since the early 1930s. A great volume of knowledge, both in service and in laboratory tests, has been accumulated about the strength, fatigue life, corrosion and failure mode characteristics of various types of built-up aluminum panels and shells. We are just beginning to accumulate such evidence about composite material. Composite materials, constructed of laminas and being anisotropic, may have different kinds of failures than can be anticipated. Therefore, there has been great hesitancy to use composites in primary structure. Now, however, there are many programs to enlarge the data base and develop analytic methods for composites. Composite flaps, rudders, spoilers, wheel-well doors, and stabilizers are being flown in military and commercial service. Over the next few years a great deal of experience with the weathering and fatigue characteristics of the material will be obtained. With the reductions of cost and the great potential savings in weight it seems likely that increasing use of composite materials will occur. It would seem reasonable that ten years from now aircraft will appear with major structural use of composites.

The weight savings of over 30% indicated in Figure III-16 for pseudo-isotropic graphite epoxy cannot be expected in a complete structure. Compromises will have to be made at fittings and joints in order to maintain the integrity of the material. Some regions may still have to be made of metal Nevertheless, one can anticipate the possibility of structural weight savings on the order of 25%. The savings in fuel from composite materials, assuming a structural weight reduction of 25% before resizing the aircraft, will be about 12%.

The effects of composites on operating costs is unclear. It will require much decreased material and fabrication costs to match current manufacturing costs. Maintenance costs might be higher. Fuel savings will be significant, reducing direct operating costs by 4% to 5%. A sensible range of possibilities is 0% to 10% reduction in direct operating costs due to composites.

Induced Drag Improvements

Another class of potential gain is the reduction of aerodynamic induced drag. Some progress in this direction has been achieved by Richard Whitcomb of NASA's Langley Research Center using well-designed endplate-like devices called winglets. A several percent decrease in drag appears possible with less bending moment increase than from simple span extensions, although all of the implications are not yet clear.

Propulsion

The history of aircraft has been closely identified with the development of aircraft propulsion In fact, improvements in specific fuel consumption and in power to weight ratios of power plants, plus the invention of new types of propulsion such as the gas turbine, are probably the most important influences in airplane development. Therefore, looking back at history, one must anticipate significant improvements in the future in propulsion. Nevertheless, at this time, there does not seem to be a great expectation of propulsion advances

The logical extension of the present high bypass-ratio turbofans is to still higher bypass-ratios This development trend would lead to lower specific fuel consumption as shown in Figure III-18 from Reference 19. The problem with the higher-bypass ratios is, however, that as bypass ratio increases, the weight per pound of thrust increases and the diameter of the engines for a given thrust increases. The result is that the drag and weight increases counterbalance the improvement in specific fuel consumption. Results of a study of the total effect of bypass ratio, Reference 19, are shown in Figure III-19. It is seen that the pounds of fuel per seat-mile and and the relative direct operating cost does not improve with higher bypass ratio but, in fact, degrades. Other studies, however, do show modest gains for bypass ratios up to 8.

On the more innovative side, the concept of regenerative gas turbines has been discussed. Although the idea of utilizing waste heat is always attractive in any power plant concept, the practical means of doing that in an aircraft gas turbine is far from clear. Therefore, one concludes that, except for small gains in efficiency due to improved compressor, turbine, and combustor design (which may in turn be permitted by improved materials), the way to significant propulsion efficiency improvements is very cloudy. On the other hand, cognizant of the continual improvements in the history of efficiency of propulsion

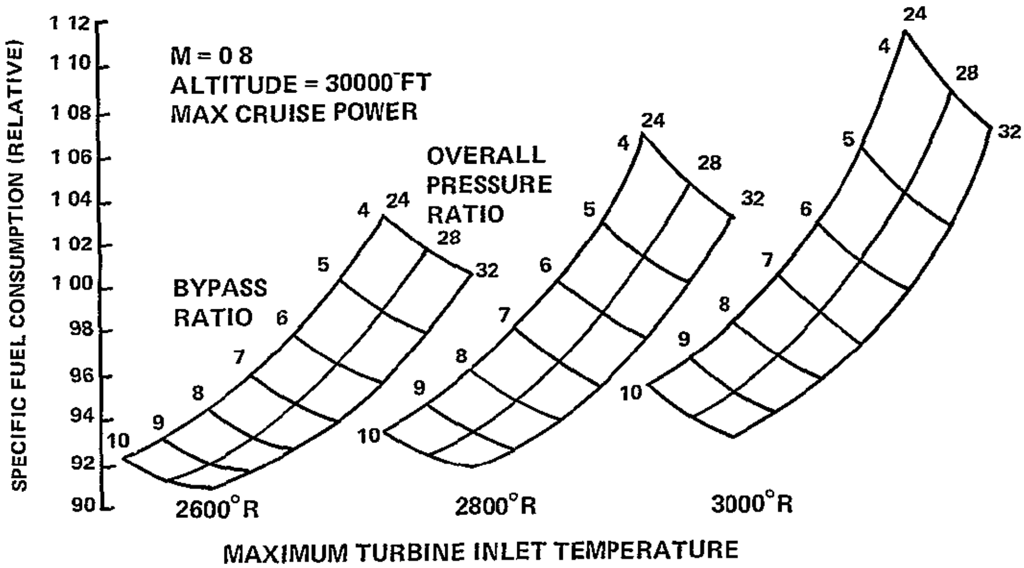

Figure III-18. EFFECT OF BYPASS RATIO ON TURBOFAN SPECIFIC FUEL CONSUMPTION

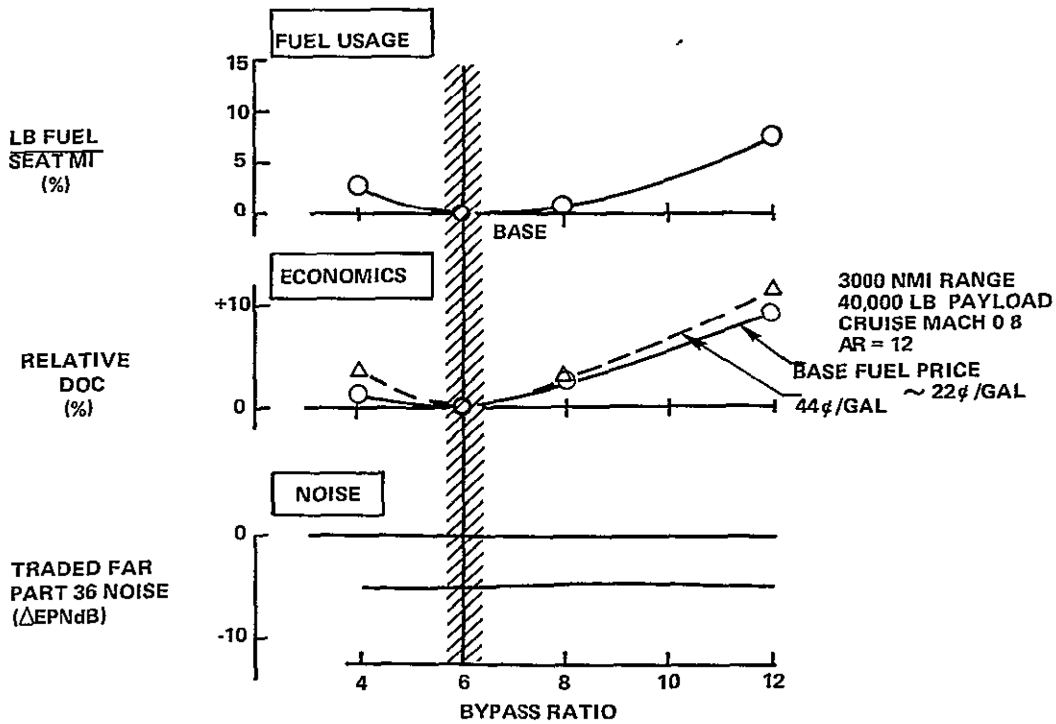

Figure III-19. EFFECT OF BYPASS ON AIRPLANE FUEL EFFICIENCY AND COST

units, and specifically of jets and turbofans, one would tend to assume that there is a possible gain on the order of 5% to 10%. Again, looking at the past, we must emphasize that this ignores the possibility of an invention.

Turboprop Powered Aircraft

New developments in an old technology plus the rise in fuel costs and the energy conservation ethic have revived sufficient interest to justify special mention of turboprop aircraft. The turboprop airframe itself is not necessarily technologically different, at a given design Mach number, from that of a turbojet. The turboprop propulsive systems offers lower fuel consumption at the expense of the maintenance cost, noise and vibration of propellers, and in the past, lower cruise speeds. Application of improved transonic airfoils, swept-blade tips, high solidity ratios obtained by using up to eight blades, and improved materials now offer improved propeller efficiencies at airline speeds around $M = 0.8$ with lower tip speeds to reduce noise. The new propeller is being called a propfan due to its resemblance to a fan.

The integration of the turboprop into an airplane involves many trade-offs and the full realization of the improved propeller performance depends upon the evaluation of these trade-offs. The potential gain is said to be up to 20% in fuel and perhaps 5% in direct operating cost with respect to current transport aircraft. What the actual gain will be after the design problems are explored is not clear. Among the design problems are interior noise due to the propellers, requiring additional fuselage weight, propeller structural and mechanical problems, the disturbance to the super-critical wing flow due to the slipstream, and the scrubbing losses of the slip stream on the surfaces behind them. If the cost gains are retained at current speeds after these matters are thoroughly explored and if the interior noise is minimized--by maintaining a clearance between the propeller tips and the fuselage of five to six feet for example--the turboprop may return to the airways. Certainly it will deserve consideration, although a step backwards to the mechanical problems of propellers and possible increased cabin noise and vibration will be difficult to take. The costs in this report do not include consideration of the turboprop since they remain very indefinite at this moment.

Combining the Advantages

From the above, it may be concluded that transport aircraft 25 years from now will be based on today's aircraft in general form, improved by aerodynamic, material, avionic, and possibly propulsion developments and with design influenced by energy costs and availability. It is therefore expected that the type of aircraft operating in the year 2000 can be visualized by combining the advantages of the various technological improvements anticipated.

The large increase in fuel costs will change the shape of future aircraft. Aircraft configurations are usually optimized for minimum cost. One of the parameters affected is aspect ratio. The optimum aspect ratio is a compromise between minimum fuel weight and cost obtained with high aspect ratio and lower structural weight and cost obtained with low aspect ratio. With higher fuel costs, optimum operating costs will occur at higher aspect ratios. The minimum fuel consumption aircraft would tend to have very high aspect ratio, excessive structural weight, and a rather high cost. If stability comes to fuel prices, aircraft design criteria are not likely to be based on minimum fuel usage but rather on minimum operating cost with the existing fuel price. In any case, the composite materials are particularly well suited to higher aspect ratio designs both because of the lower structural weight and because the high elastic modulus will reduce weight penalties that might have to be applied for aeroelastic reasons as the span increases.

The improved transonic airfoils complement this scenario very well For any design speed in the transonic region, the lower permissible sweepback angle and/or higher wing thickness ratio increase effective wing stiffness, favorable for the aeroelastic problems of high aspect ratio, and reduce the basic wing weight level The combination of the new rear loaded transonic airfoils and composite structural materials will permit the aerodynamically efficient high aspect ratio wings required to optimize economics with high fuel cost. The fuel savings that can result from the improved transonic wing, when used at today's cruise speeds, and aspect ratios, is about 5%, Figure III-20 The additional fuel savings in fuel from composite materials will be about 12%. The total fuel advantage is on the order of 16%. If, at present cruise speeds, the aspect ratio is now increased to an optimum cost value with the thicker airfoils and lighter materials, a further fuel reduction of up to 15% will be obtained

Combining all of the above potential with propulsion and winglet advances may then lead to fuel consumption reductions of:

95	x	.88	x	.85	x	.92	x	.97	x	.96	= 0.61
airfoils		composites		aspect ratio increases		propulsion		winglets		active controls	

or a reduction of about 39%. However, it is unlikely that all of these will be achieved without reducing the effects of other elements For example, the impact of winglets on high aspect ratio aircraft may be reduced Design for Mach numbers that favor fuel consumption will reduce the trim drag, the further reduction of which is a portion of the active control gain A combined gain of about 75% of the potential gain seems

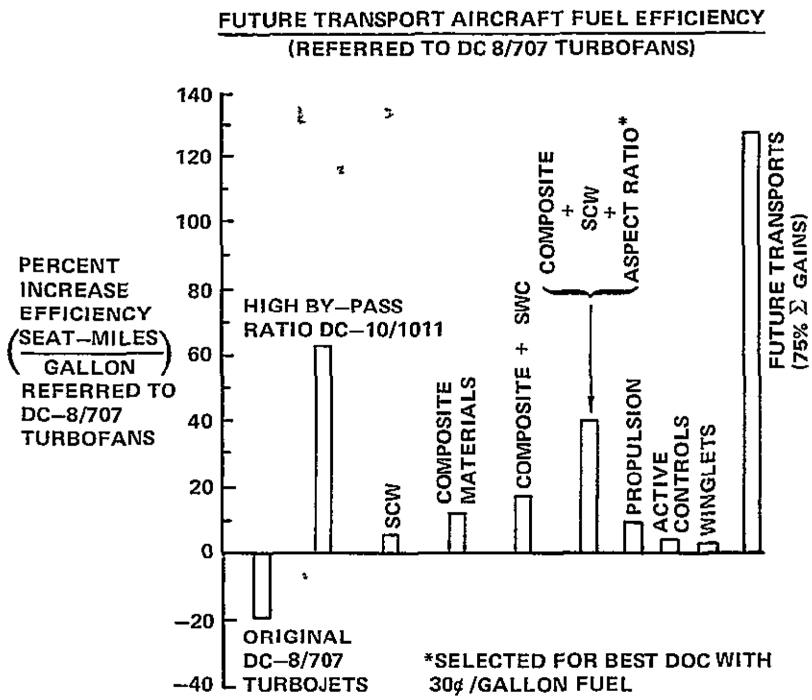

Figure III-20 FUTURE TRANSPORT AIRCRAFT FUEL EFFICIENCY (REFERRED TO DC-8/707 TURBOFANS)

reasonable The total reduction in fuel used is then 29% and the increase in seat-miles per gallon is 40%, i.e., 1/0.71 = 1.40.

Figure III-21 shows the fuel efficiency of existing and future aircraft in terms of seat-miles per gallon of fuel. The B-747, DC-10, and L-1011 type aircraft with high bypass ratio engines offer improvements in passenger-miles per gallon of 50% to 60% over the 707/DC-8 turbofan airplanes and up to 100% over the 707/DC-8 original jet airplanes The additional improvement of the order of 40% possible with the new rear-loaded transonic airfoils, composites, active controls, and correspondingly increased aspect ratio can bring the combined improvement in passenger-miles per gallon of future aircraft as compared to the original 707/DC-8 turbojets to as high as 185%, Figure III-20. Inversely, the fuel consumption per seat-mile is lower for today's widebody airplanes by 34% to 39% compared to standard 707/DC-8 turbofan airplanes and about 47% to 50% compared to the original jets and will in the future be 56% below the requirements of today's 707/DC-8 turbofan airplanes and 65% below the original jets.

The "expected" curve of fuel efficiency in Figure III-21 is shown as the center of a band indicating a ±10% tolerance The tolerance is related to the degree of success in applying composites and the propulsive unknowns.

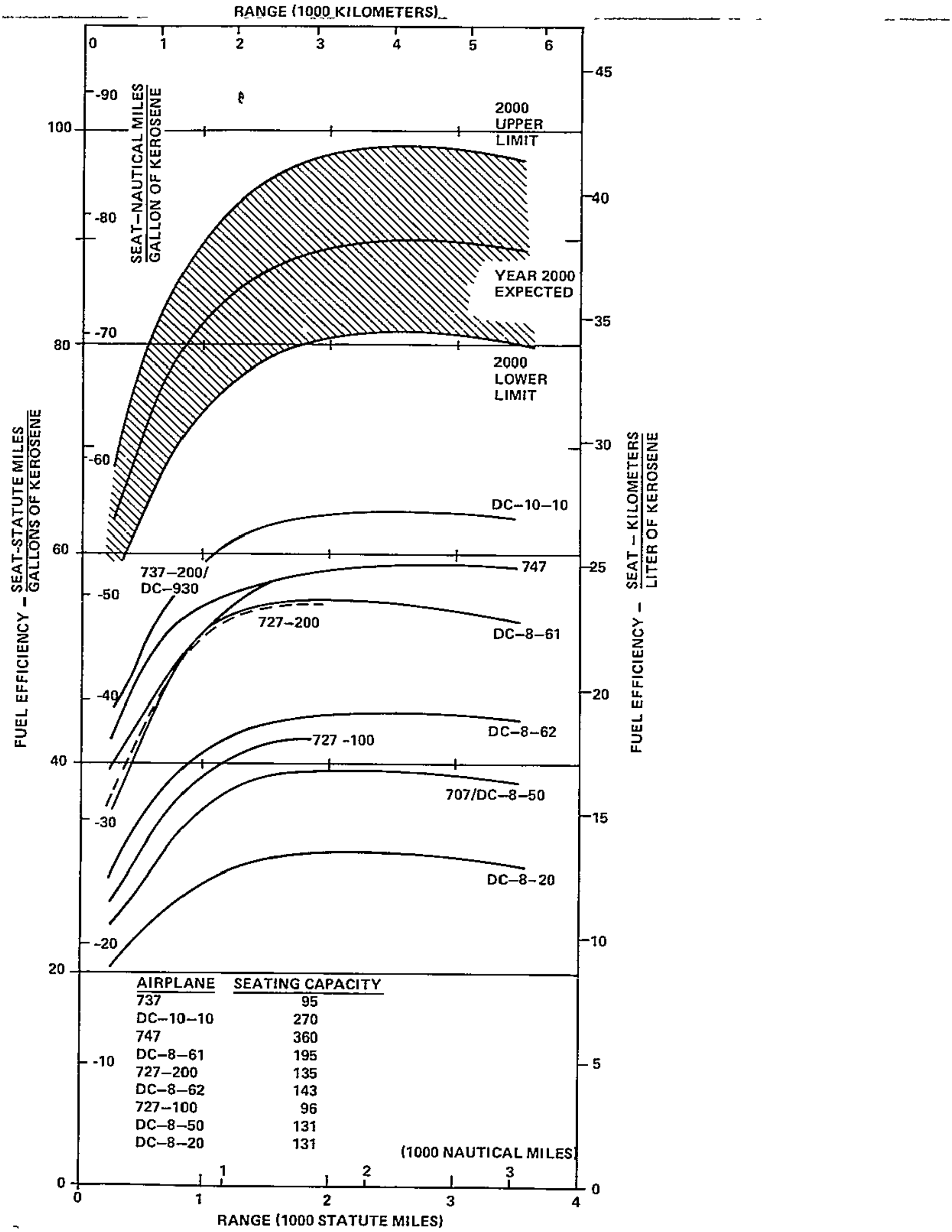

Figure III-21. AIRCRAFT FUEL USAGE (Current Values Based on United Air Lines Flight Planning Charts)

The total effect of technological advances on the direct operating costs of aircraft is very difficult to analyze. Those advances that reduce fuel consumption can, of course, be calculated. But one of the major potential impacts is the use of new materials and here the problem is the current high price of both material and fabrication. In recent years, however, there has been a very significant reduction in material price and a great deal of knowledge gained in the fabrication of composite material so that it seems a reasonable guess that the price of an airplane built out of composites may be very close to the cost with current construction. In Table III-2 is a summary of cost increment estimates by various aircraft companies with respect to various technological improvements, such as composite materials, improved transonic airfoils and active controls. Based on a review of these values, plus the author's judgment, a range of reasonable estimates of direct operating cost improvement for each technology has been estimated as shown in Table III-2. It is from this band that the possible direct operating cost impacts of the reductions of 6% to 18% has been arrived at with a mean value of 12%. This band is shown on the direct operating cost curve in Figure III-22.

Table III-2

TRANSPORT AIRCRAFT DIRECT OPERATING COST
CHANGES DUE TO ADVANCED TECHNOLOGY

Technology	Predicted Cost Changes			Reasonable Range
Composite Materials	-1/2% to +3.5% Douglas	-8% General Dynamics	-15% Lockheed	0% to -10%
Improved Transonic Airfoils	-4% Douglas	-6% General Dynamics $\Delta M_{cr} = +.08$	-4.2% Lockheed	-4%
Active Controls	-4% Douglas	-3% General Dynamics	-5% to -8% Lockheed	-2% to -5%
Active Controls + Composites		-13.6% $\frac{\text{Lockheed + General Dynamics}}{2}$		
Σ All Technologies	-11% Douglas (R.E. Black paper)			-6% to -18%

Direct Operating Costs

In assessing operating costs, all data have been corrected to 1974 dollars. In evaluating various transportation modes, the effects of inflation can either be applied to all of them or ignored in terms of getting a modal split. Of course, in assessing total transportation usage, the relative cost of transportation, with respect to other possible uses of disposable income, is a significant factor. In the technology section, however, we have limited the goal to determining costs based on 1974 dollars

The direct operating costs of various representative types of today's aircraft have been determined from comparative data generated by the Douglas Aircraft Company.[20] These data are shown in Figure III-22 in terms of dollars per mile and in Figure III-23 in terms of dollars per seat-mile, both in 1972 dollars. The number of seats in the aircraft are based on representative mixed-class configurations as currently operated by the airlines. It should be noted that the direct operating cost per seat-mile can be reduced by approximately 10% by using all coach interiors. These would definitely be appropriate to commuter runs

In Figure III-24, a cost scaling chart for passenger capacity shows the comparative direct operating cost of aircraft as a function of passenger capacity. This chart is based on correlating the results from many different consistent airplane design studies by Lockheed, Boeing, and Douglas. The correlation shows that regardless of design field length and propulsion-system type or range, as long as a family of various size aircraft are designed with completely consistent requirements for field length, range, and speed, the effects of changing from one capacity to another can be normalized to one curve This makes a very useful tool so that we can work with a curve of direct operating cost versus range for one airplane size and then convert to any other desired airplane size through the use of this tool. Using Figure III-24, the direct operating cost results from specific airplanes, shown on Figure III-23, are normalized to a capacity of 150 passengers in Figure III-25. If all of the airplanes in Figure III-25 had been designed to the same rules, the data for all of them should fall together. But, as we see, the longer-range airplanes show a higher normalized direct operating cost. This is to be expected since the longer range requires higher gross weight, larger engines, and larger wing and tail areas in order to carry the fuel for the longer range. The twin-engine aircraft fall a little lower in cost than might be anticipated. This is because of certain operational and service advantages that seem to accrue in operation to twin-engine airplanes and therefore reflect a true impact, particularly in short-range operation where the twins are very suitable

An envelope is then drawn reflecting the lowest direct operating cost versus range on Figure III-25. After correcting the data to 1974

dollars using inflation factors* for direct operating costs obtained from Douglas Aircraft Company, this envelope is plotted as the direct operating cost versus design range in 1974 dollars for aircraft with a capacity of 150 passengers, on Figure III-26. The curve on Figure III-26 is then reduced for potential direct operating cost advantages to be found from technological improvements in the future. These cost advantages cannot be pinpointed, of course, but have been defined above as a most probable reduction of 12% plus or minus 6%. Both the band and the best estimate is shown on Figure III-26. This best estimate for technology in the year 2000, in terms of 1974 dollars, can be combined with the curve in Figure III-24 to adjust for the effects of capacity on direct operating costs in order to determine the direct operating cost for any size aircraft in the year 2000.

The fuel cost in 1974 dollars is about $0.24 per gallon To correct for the effect on direct operating cost of fuel price changes, in 1974 dollars, Figure III-27 is provided. The data are based on DC-10 calculations from References 21 and 22

The components of direct operating cost vary with fuel price, airplane pricing policy, and airplane design characteristics A good approximation for typical transports, with $0.24 per gallon for fuel, is given in the following tabulation:

Fuel	34 0
Depreciation	25.0
Maintenance	18.5
Crew	16 0
Insurance	6.5
	100 0%

*1972 to 1973 = 1 149
1973 to 1974 = 1.150

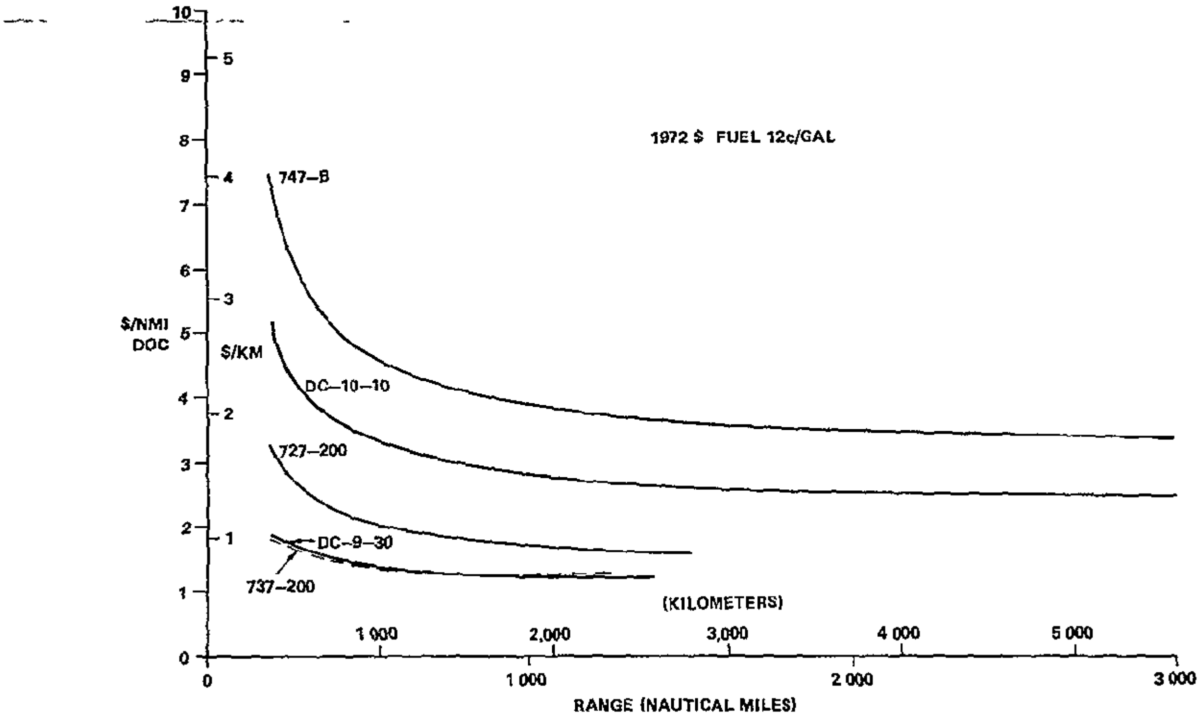

Figure III-22. AIRCRAFT DIRECT OPERATING COSTS

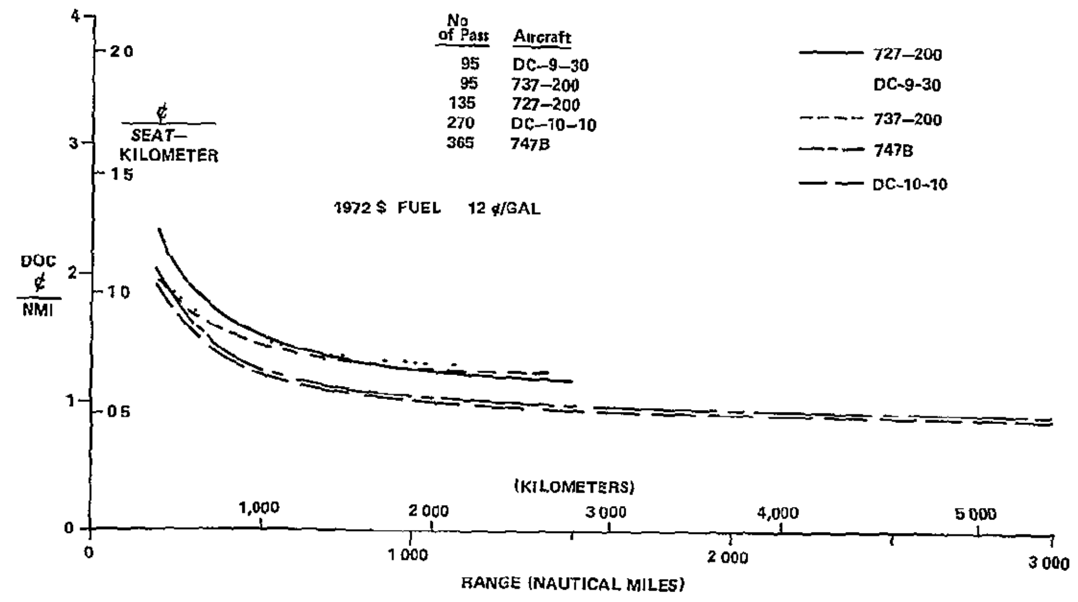

Figure III-23. AIRCRAFT DIRECT OPERATING COSTS

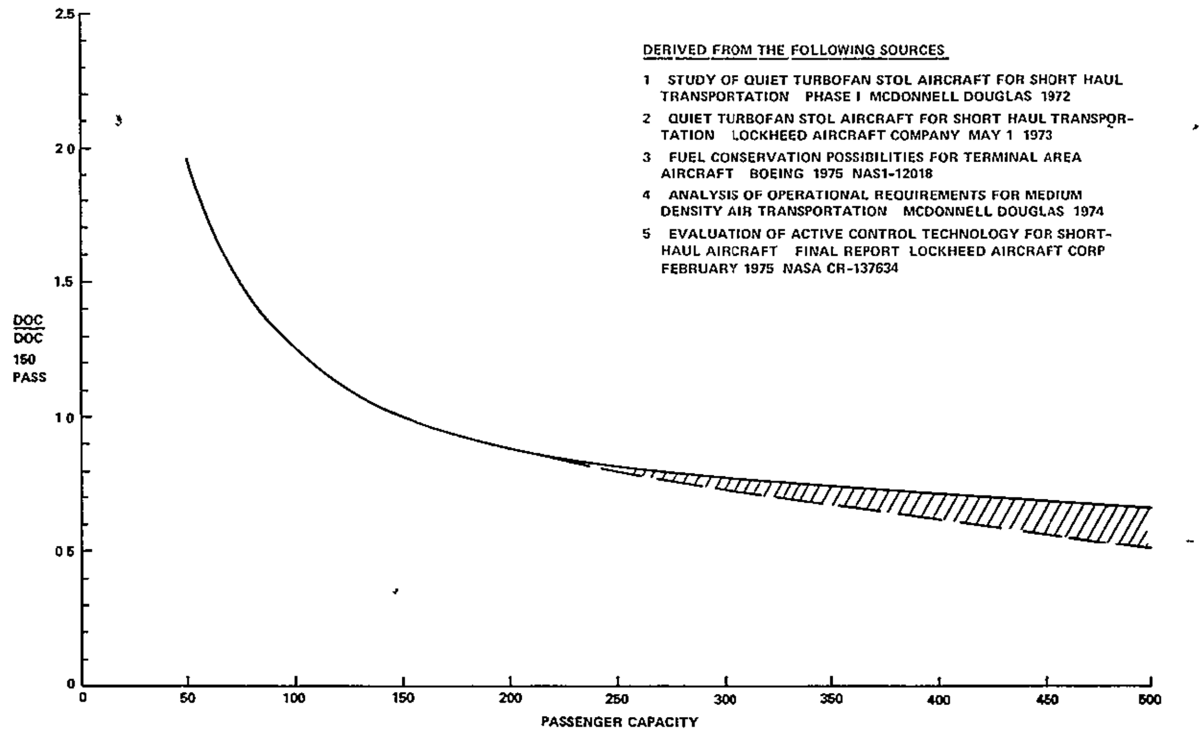

Figure III-24. PASSENGER CAPACITY CORRECTION FOR AIRCRAFT DIRECT OPERATING COSTS

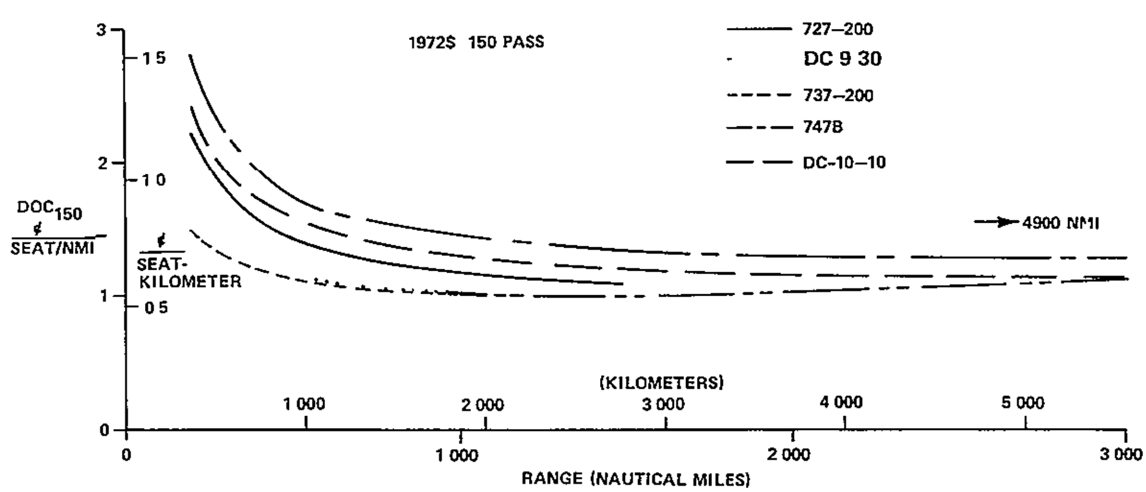

Figure III-25. AIRCRAFT DIRECT OPERATING COSTS

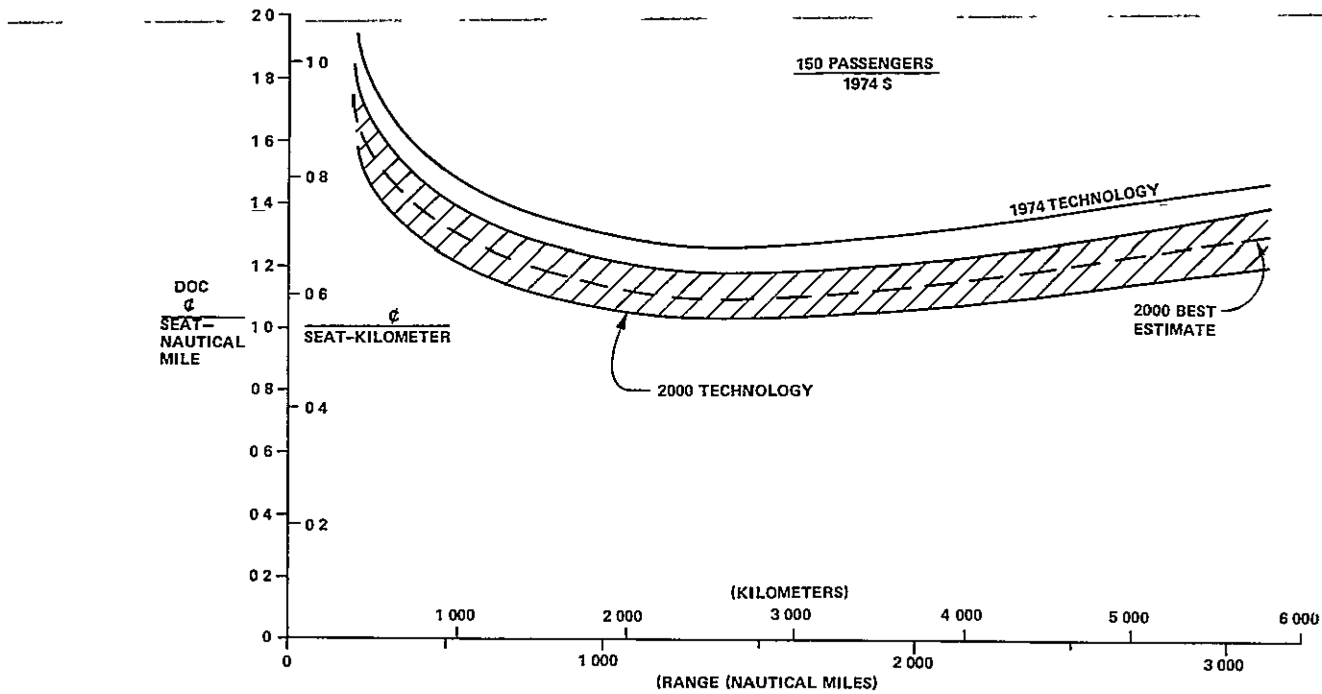

Figure III-26. AIRCRAFT DIRECT OPERATING COSTS

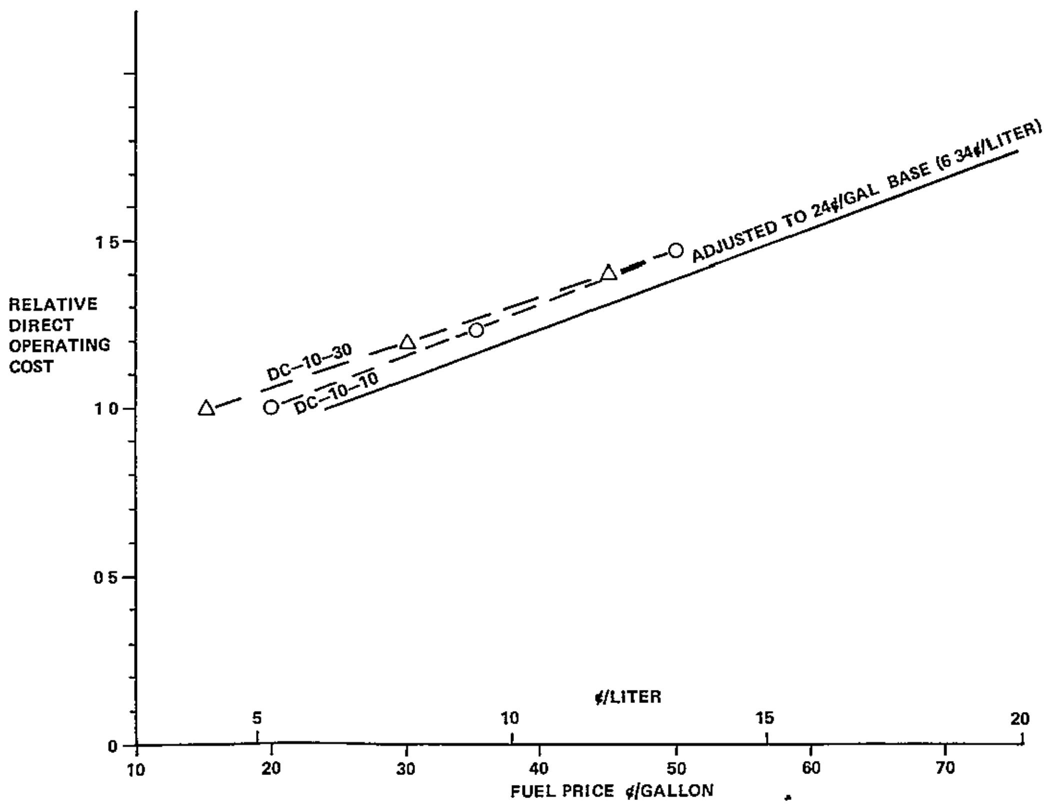

Figure III-27. EFFECT OF FUEL COST ON DIRECT OPERATING COST

Aircraft Investment Cost

The purchase cost of transport aircraft in terms of 1972 dollars per seat, based on mixed-class seating, is plotted for several existing aircraft in Figure III-28 These are based on representative mixed-class interiors. Cost involves not only labor and materials but also the current pricing policy and, therefore, the indicated scatter should not be a surprise. An average fairing has been put through the data. Figure III-29 illustrates some price variations between the years 1972 and 1974, as well as a theoretical price indicator based on variations in material and labor cost indices Since the actual price should lag the material and labor cost indices somewhat we have chosen the variation in DC-10 and 747 prices and applied them to the airplane-price-per-seat data for 1972 to obtain 1974 prices. In using these data to obtain investments, 30% should be added for equipment and spares. For all-coach or commuter applications, the cost per seat should be reduced approximately 10%.

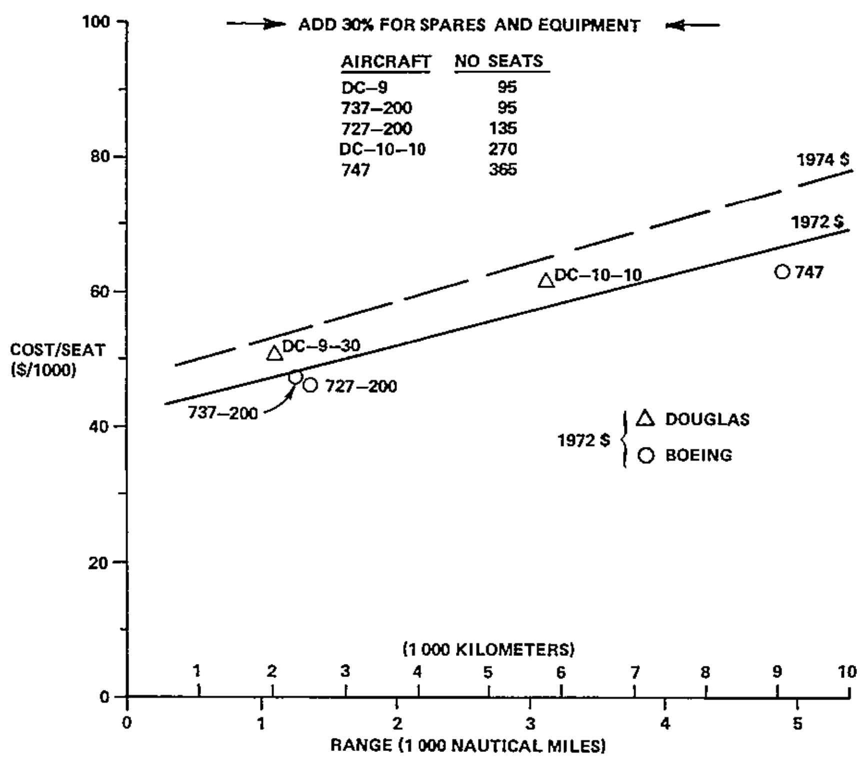

Figure III-28. AIRCRAFT COST PER SEAT--MIXED CLASS INTERIORS

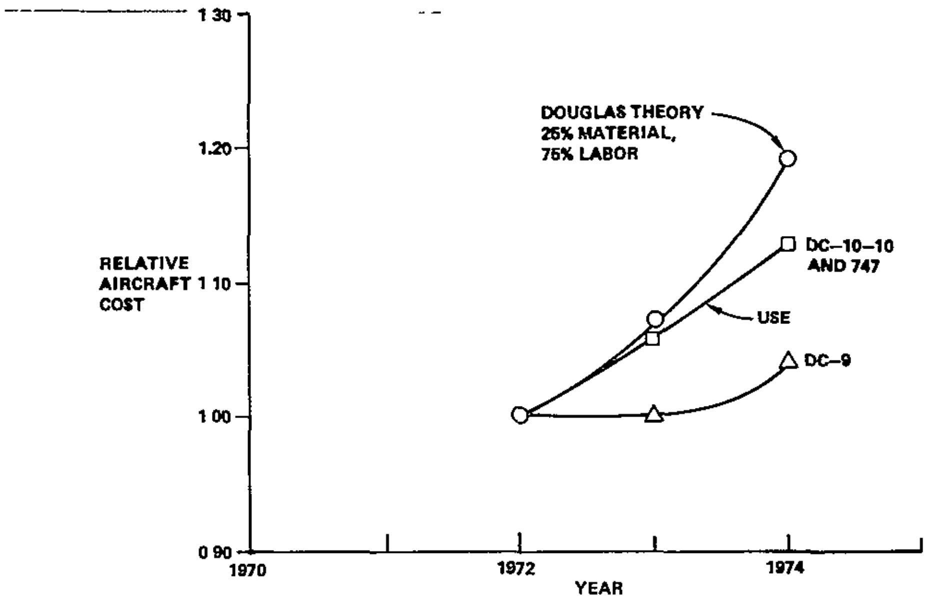

Figure III-29. AIRCRAFT PRICE INFLATION

Indirect Operating Costs

Indirect operating costs have been obtained by analyzing the data generated by an aircraft committee on indirect costs using statistical airline data. Applying the method to representative aircraft has led to fitting the data with the expression

$$IOC_{1000\ nmi}(\$/nmi) = -.04 + .00129\ Wg + .00119\ N_p + .0127\ N_p\ L_F$$

(domestic routes)

where

$$Wg = \frac{\text{Maximum Takeoff Weight (lb)}}{1000}$$

N_p = Passenger capacity

L_F = Load factor

along with a correlation showing how the IOC, in terms of dollars per nautical mile, varies with range as shown in Figure III-30. The equation, and the curve adjusting for range, has been used to determine the indirect operating cost for several airplanes at 50% and 60% load factors. Those data are plotted in Figure III-31 in terms of indirect cost per passenger versus range. The data upon which this method is based were

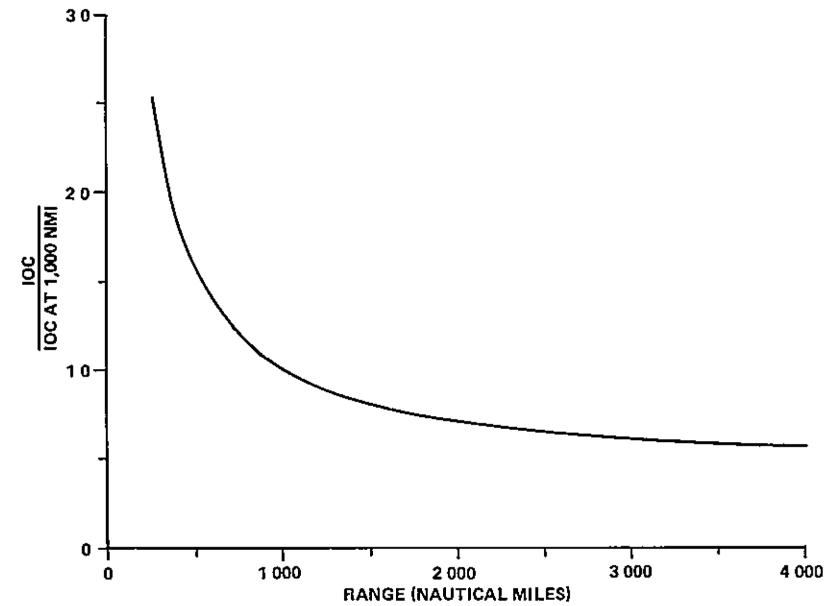

Figure III-30. EFFECT OF RANGE ON INDIRECT OPERATING COSTS

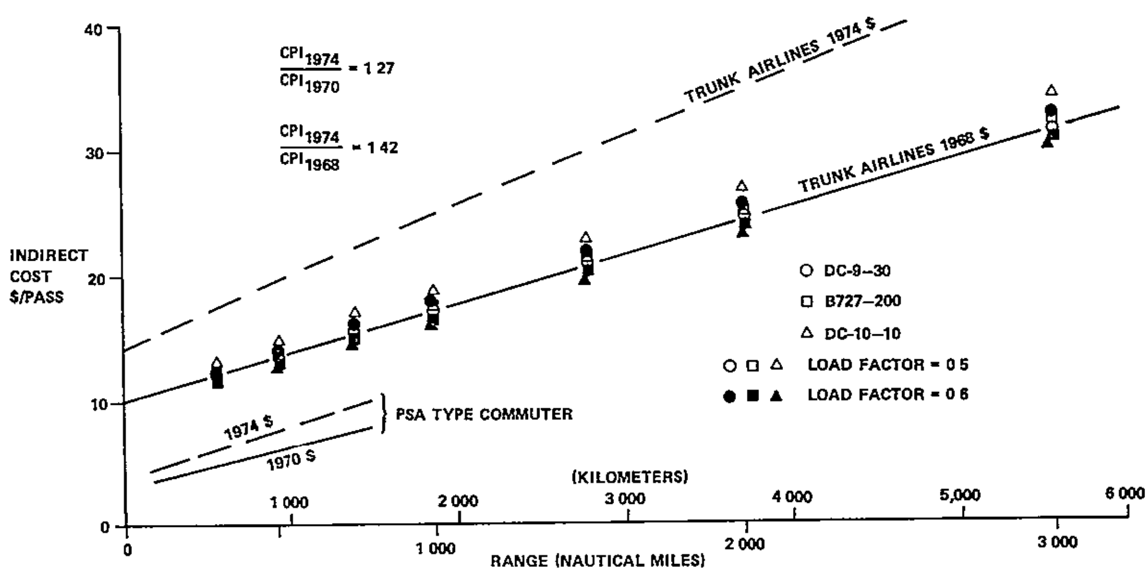

Figure III-31. AIRCRAFT INDIRECT OPERATING COSTS

for the year 1968. To provide a basis for adjusting the costs to current levels, the consumer price index (CPI) variation during the period under consideration is plotted in Figure III-32. The ratio CPI (1974)/CPI(1968) has been used to correct the indirect costs from 1968 to 1974, as noted on Figure III-31.

Also shown in Figure III-31 are data for the indirect cost of a highly efficient commuter airline such as Pacific Southwest Airlines (PSA). The equations for these commuter indirect costs are from Reference 7.

$$\text{Indirect Costs (cents per available seat-statute-mile)} = l_f\left(\frac{300}{d} + .625\right)$$

where

l_f = load factor

d = air distance in statute miles

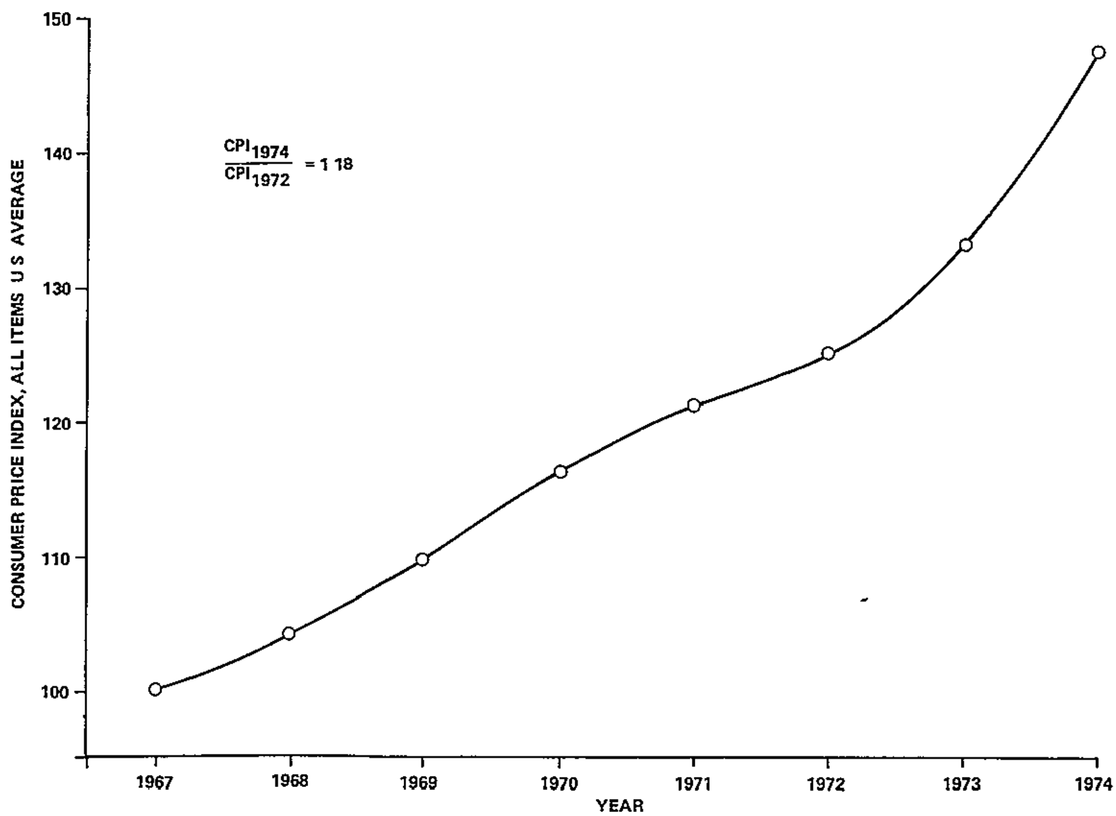

Figure III-32. CONSUMER PRICE INDEX

This equation is based on the year 1970. The consumer price index data on Figure III-32 have been used to bring the PSA indirect costs up to the 1974 level.

Block Time

A representative curve of block time versus range for present aircraft speeds is shown in Figure III-33. Because of the emphasis on fuel, it does not appear likely that there will be any substantial change in speed in the next couple of airplane generations which will encompass the period to the year 2000. Therefore, this block time curve is believed to be typical of future air travel.

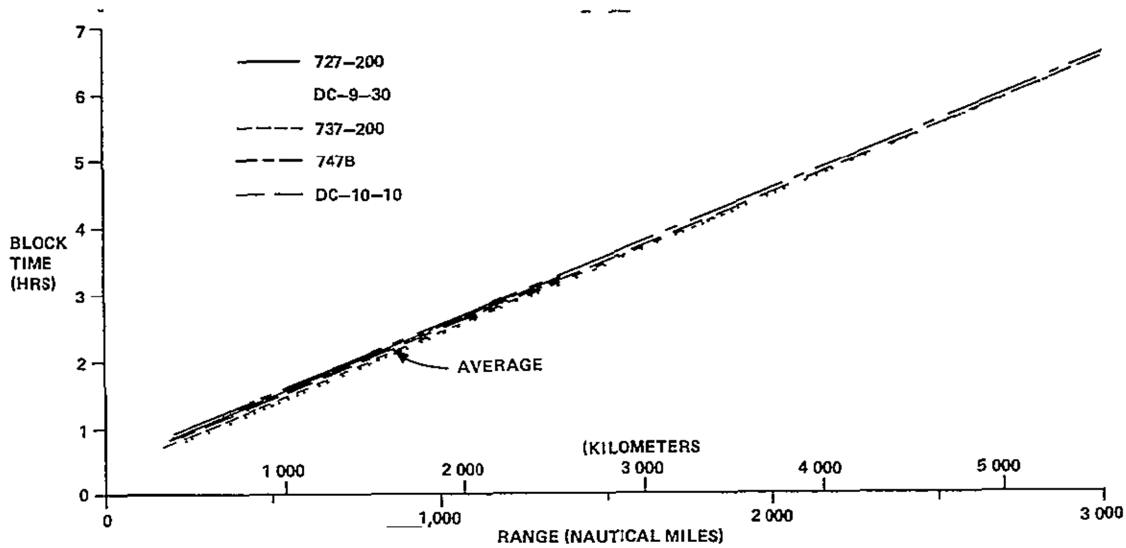

Figure III-33. AIRCRAFT BLOCK TIME

Noise

The seriousness of the aircraft noise problem is well known. Since about 1956, efforts by industry and NASA have been directed at the causes of aircraft noise and possible means of alleviation. Figure III-34 illustrates the principal noise sources within the engine. Substantial progress in understanding the relationships between engine design and flow characteristics has been achieved. The high bypass ratio (BPR = 6) turbofan engines in the current widebody transport aircraft are substantially quieter than the early turbofans (BPR = 1) and, of course, even quieter than the original 707 and DC-8 turbojet aircraft.

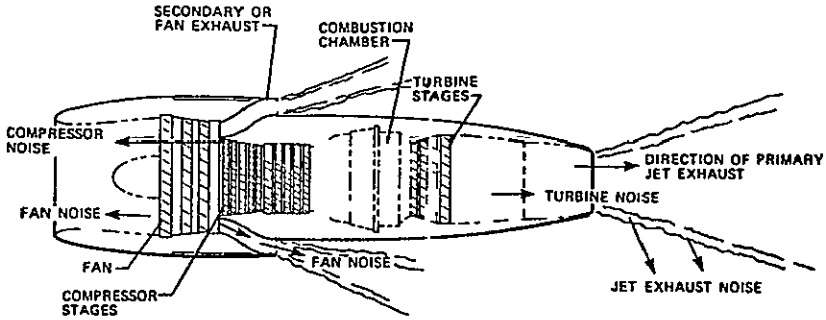

Figure III-34. TURBOFAN ENGINE NOISE SOURCES

In turbojet aircraft, the jet mixing was the dominant noise source. Since the jet noise energy is proportional to the eighth power of the velocity, reduction of jet velocity was the most powerful means of reducing noise. This effect is shown in Figure III-35 where the reduction in jet exit velocity from about 2000 feet per second for the jets to about 1600 feet per second for the early turbofans to 1200 feet per second for the high bypass ratio turbofans has a large favorable effect on jet noise. Other noise sources such as the fan then become dominant. These were in turn treated as indicated in Figure III-36 and by sound absorptive material (SAM) lining the inlet and exit ducts to reduce fan and turbine noise

The Federal Air Regulations dealing with noise, FAR Part 36, are summarized in Figure III-37 The noise levels, in terms of effective perceived (EPN) noise levels are shown for the early and later turbofan aircraft. The noise is measured at 3.5 nautical miles from the start of takeoff for the takeoff case, 1.0 nautical miles before the runway threshold for the approach noise, and 0.25 nautical miles (0.35 nautical miles for four-engine aircraft) to the side of the runway for sideline noise. The marked improvement between 707/DC-8 aircraft and the DC-10 is apparent.

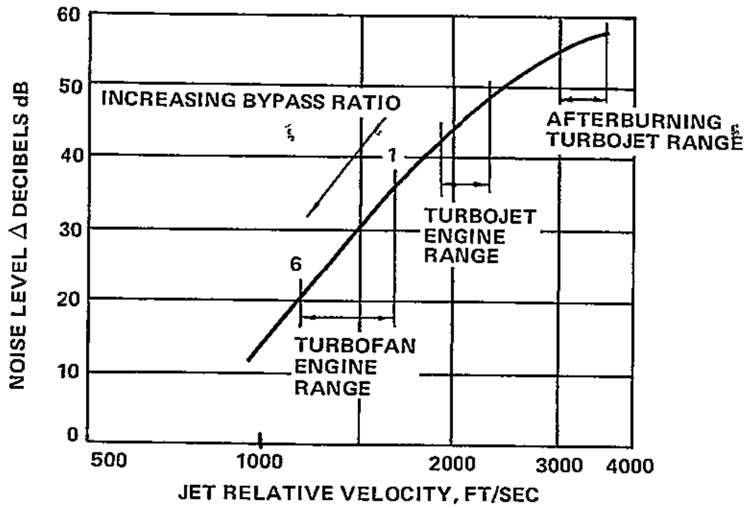

Figure III-35. EXHAUST NOISE LEVEL VS. JET RELATIVE VELOCITY

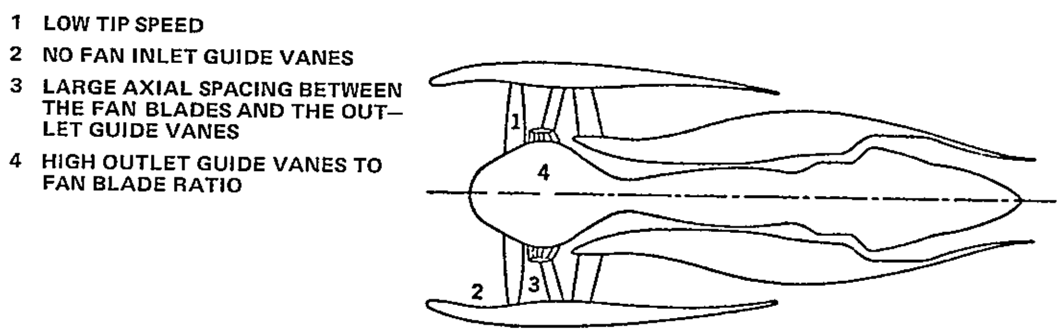

Figure III-36. NEW TECHNOLOGY FEATURES OF THE HIGH-BYPASS-RATIO TURBOFAN ENGINES

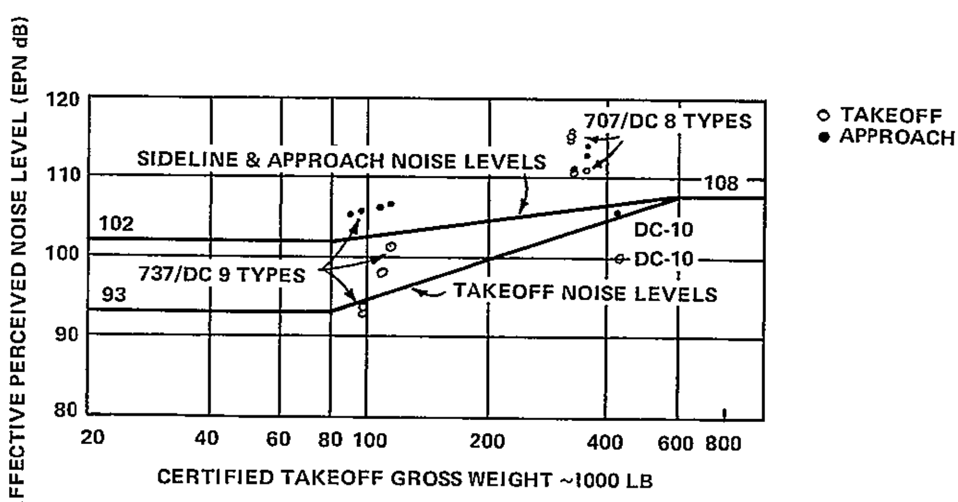

Figure III-37. NOISE REQUIREMENTS FROM FAR 3

Another way of measuring the noise difference between aircraft is shown in Figure III-38 where the noise footprints or contours on the ground of equal noise, in this case 90 EPNdB (effective perceived noise decibal) are shown for the DC-8-61 and the DC-10-10 at maximum takeoff weights. The ground area affected by 90 EPNdB or more is 48.61 square miles for the DC-8 and 7.17 square miles for the DC-10, a reduction of 85%. This method of evaluating noise reduction is somewhat misleading. Although the area impacted by a given noise level is reduced by 85%, the subjective noise at any point is reduced by somewhat less, about 60%. This is, of course, still a very large reduction.

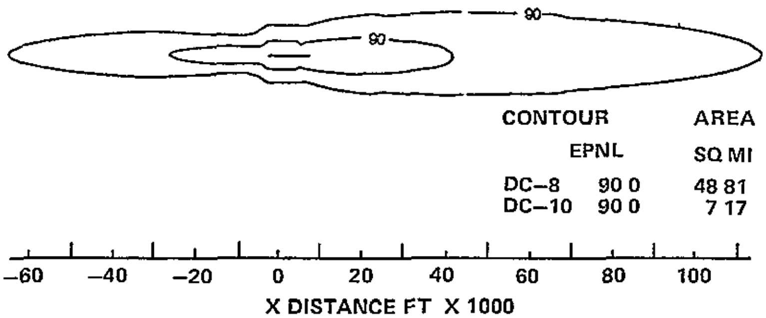

Figure III-38. NOISE CONTOURS FOR THE DC-8 AND DC-10

Increasing bypass ratio will further reduce jet noise, but the other engine noise sources become critical Improved sound absorptive liners are probably possible. Even very successful development of such liners may yield only a 2 to 3 decibal reduction in overall noise because noise sources contained in the core of the engine appear to be only slightly

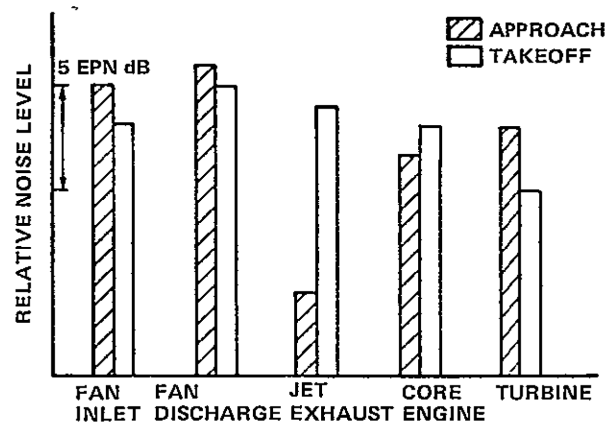

Figure III-39. TYPICAL HIGH-BYPASS-RATIO ENGINE COMPONENT NOISE DISTRIBUTION

less intense than current fan noise, Figure III-39. Core noise includes burner or combustion noise and nozzle-lip-generated fluctuating pressure. At present, no means of controlling these sources are known About 5 to 10 dB below the levels attainable with improved--but not yet demonstrated--liners, a different noise source, aerodynamic noise, appears.

Figure III-40 shows its origin. Research is now under way to study this source and attempt to design aircraft with reduced aerodynamic noise. Figure III-41 indicates that the aerodynamic noise level lies about 10 db below the present FAR Part 36 regulatory requirements.

The current prospect is that much research and development will be required to obtain noise levels more than 5 dB below the DC-10/L-1011 noise levels.

In spite of the difficulties of obtaining large further reductions in aircraft noise, the implementation into the airline fleet of present DC-10/L-1011 noise technology, various operational improvements, such as takeoff power cutback after reaching a safe height and the two-segment approach flight path, and the further advances expected in a future advanced-technology twin-engine aircraft for short- and medium-range use, such as the proposed Douglas DC-X-200, can lead to very large reductions in the community noise impact Pending the replacement of the existing fleet by DC-10/L-1011 technology, significant gains are possible by retrofitting 737s, 727s, and DC-9s with sound absorbent materials (SAM) in the engine nacelles and/or modified JT8D engine with new fans (REFAN).

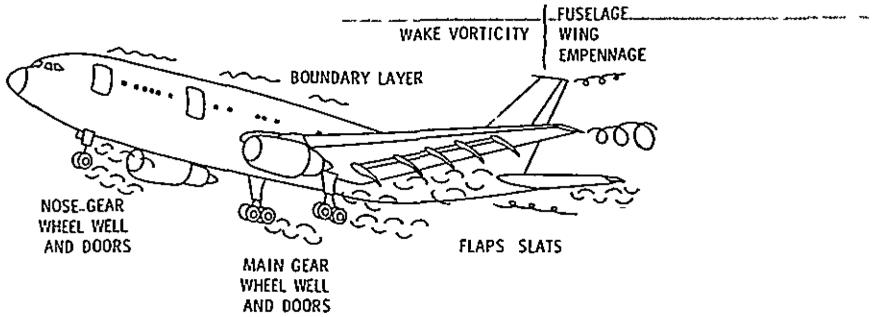

Figure III-40. NONPROPULSIVE NOISE SOURCES

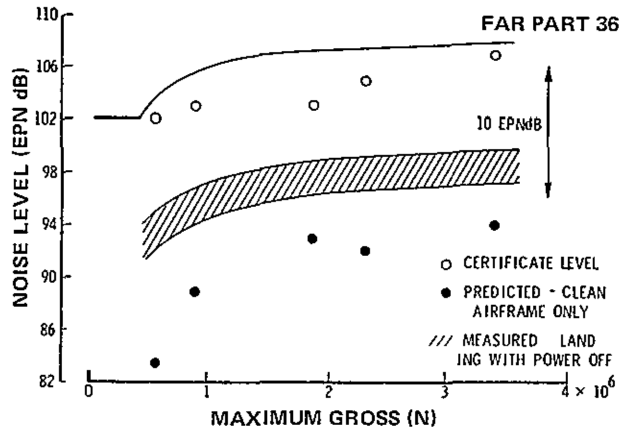

Figure III-41. APPROACH NOISE OF CURRENT AIRCRAFT

The results of the above are summarized in Figure III-42 from Reference 26. In Reference 26, a detailed study of noise impacts at one airport were intensively studied. Similar results may be expected at other sites. Figure III-42 shows the progressive reduction of community noise annoyance as the various strategies listed above are applied The long term prospects look very favorable.

General Aviation

Air transportation technology has been discussed up to this point in terms of commercial transport aircraft There is a small segment of air transportation attributable to the general aviation field. In terms of activity, such as the number of landings and takeoffs, general aviation activity is very large indeed. However, most of the general aviation activity can probably be more properly related to sailboats or power-boats than to intercity transportation. A large percentage of private flying is recreational in nature rather than for transportation The percentage of all intercity passenger-miles attributed to general aviation is 0.8%.[27] This falls into several very different categories ranging from the use for transportation of two- and four-place private aircraft to the use by corporate owners of turboprop and jet-powered aircraft such as the Jet Star, Sabreliner, Cessna Citation, Lear Jet and

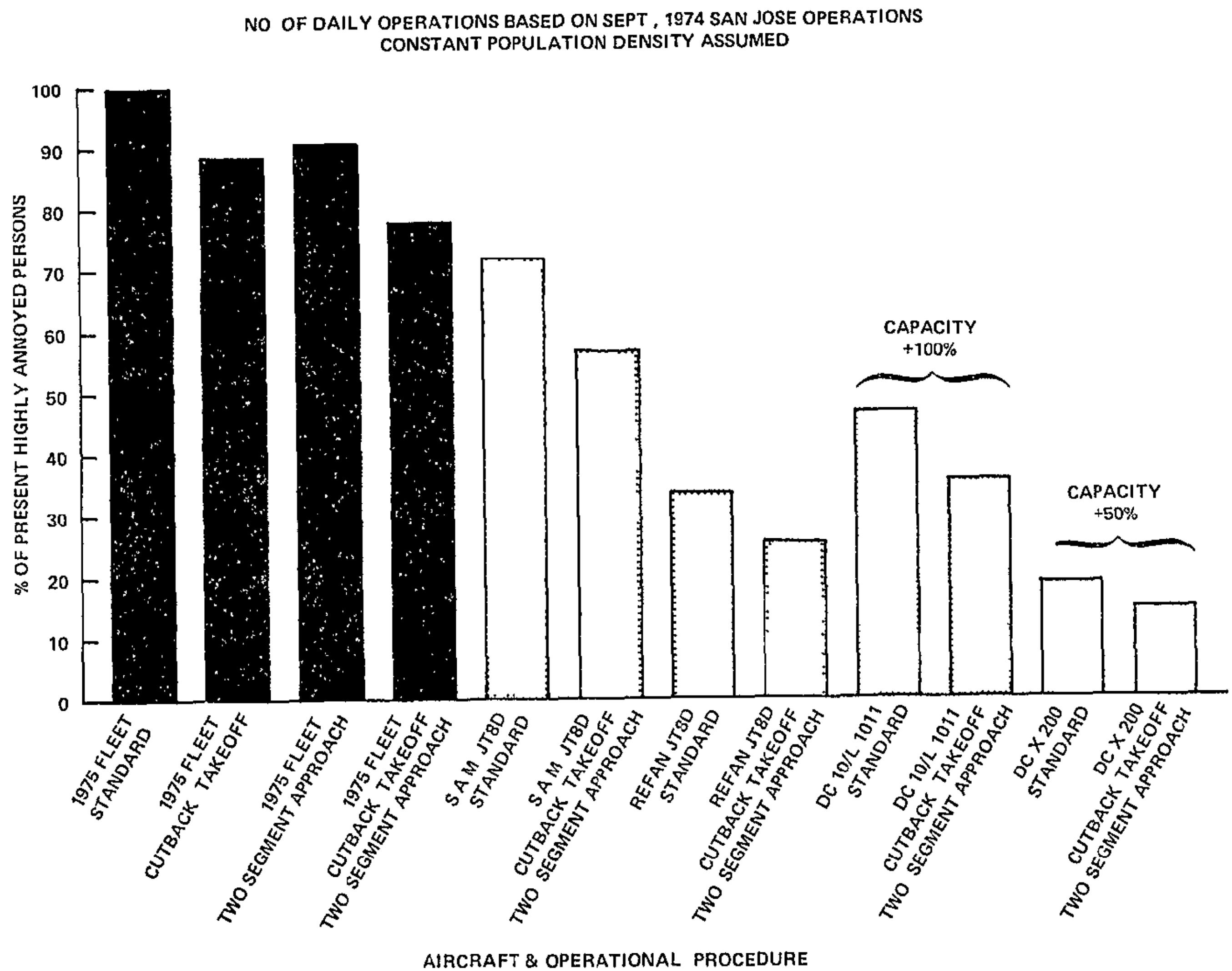

Figure III-42 SUMMARY OF POTENTIAL COMMUNITY NOISE IMPACT IMPROVEMENTS

Jet Commander for intercity transportation purposes. To those who frequently make trips to locations near small cities off the primary commercial travel routes, the general aviation aircraft provides a very important service.

The technology of general aviation ranges from the sophisticated jets that are no more than a few years behind the technology of the most advanced commercial transports to the small private planes that have changed relatively little technologically in 30 or 40 years. Recently, NASA has developed a significant program to bring the fruits of improved aerodynamic design to the smaller general aviation aircraft. Although there are some special requirements which dictate different developments to serve the needs of low Mach number general aviation aircraft, much of the technology applicable to the large commercial aircraft could be applicable to the general aviation aircraft. Sometimes the cost of development and implementation of the new technology is not justified because of the low utilization of general aviation aircraft. For example, if a development that saves 5% in fuel has a large initial cost, an airplane that burns that fuel 3,500 hours a year does not take long to return the value of the additional investment, whereas general aviation aircraft with much lower utilization might never return the initial investment. Therefore, these aircraft are in a different category.

In any case, the small percentage of intercity transportation provided by general aviation aircraft and the fact that the most significant of these aircraft are the more sophisticated, larger types used by corporate owners and likely to have most of the technology available from the larger aircraft means that the important technological developments in aviation will funnel through to the smaller aircraft whenever the cost is justified

No data on operating costs of general aviation aircraft are given both because of the very small percentage of total intercity travel carried by this mode, and because in most cases, the use of aircraft fall into either the class of corporate expenses not necessarily decided upon in a cost effectiveness analysis or by individuals for whom the trip is a mixture of recreation and a true travel requirement.

Safety

Safety is an essential ingredient in any transportation system. The safety of air transportation has generally improved over the past 30 years although occasionally there is a year in which the trend is interrupted by by an unfortunate coincidence of disasters. New technology usually improves safety in the long term but the initial use of a new technology often poses a threat to safety. Any new device may involve some element that can lead to failures that have not been foreseen With this awareness well in mind, both the aircraft industry and the monitoring agency, the FAA, study carefully the possible problems that may be introduced by

any new device or technology, and through extensive failure analysis to make sure that no single failure can cause a serious accident. This process is usually quite successful although experience has unfortunately shown that advancing the state of the art frequently involves the catastrophic discovery of an unforeseen hazard. The cost improvements in air transportation have been attained after allowing for the necessary items of design and construction that had to be added for safety as each new development came along. Therefore, it can be assumed that the cost trends we have generated include such allowances.

Figure III-43 shows the trend of safety for air transportation, rail, bus, and automobile transportation taken from Reference 27

The ever increasing use of air and auto modes shows that the inherent risks are accepted by the users as tolerable levels of risk. This in no way diminishes the need and the duty of the manufacturing industry, operators, and government to try to further reduce the risk of accident In the air mode, use of automation in the air traffic control system; on-board warning systems, such as the ground proximity warning systems now being installed; and ever increasing work in human factors to minimize misunderstanding and misinterpretation of instrument displays by the crew; are among the major research areas that need continuing strong effort.

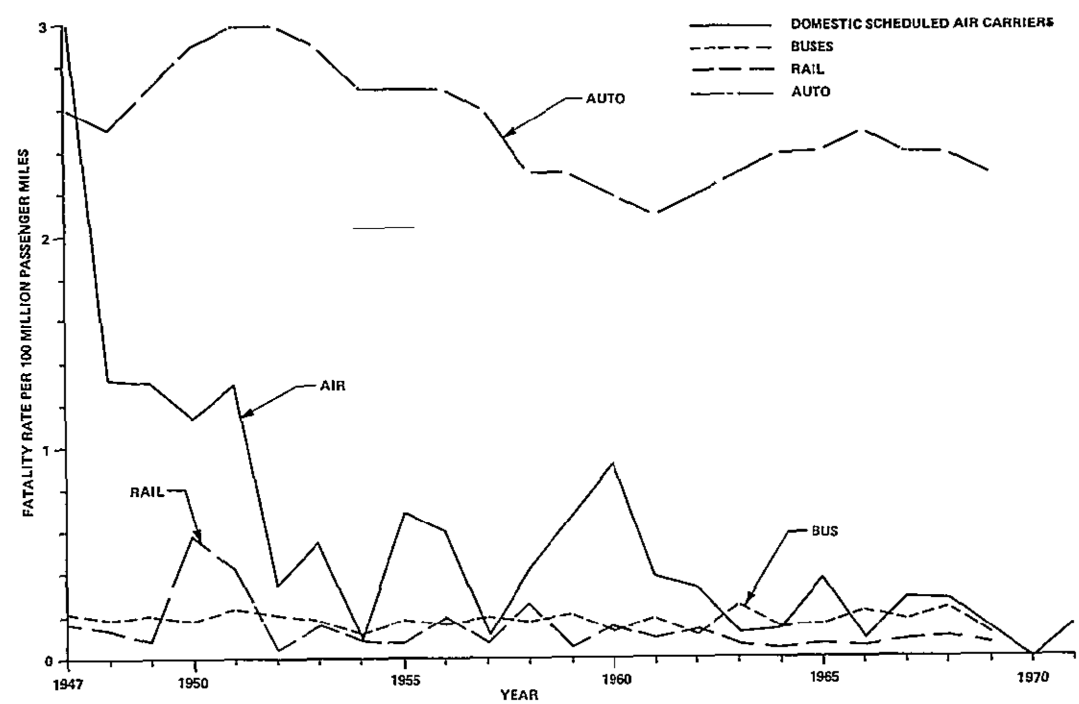

Figure III-43. RELATIVE SAFETY OF INTERCITY TRANSPORT MODES

Air Traffic Control Systems

David R. Israel
Formerly Federal Aviation Administration

Current Status of the Air Traffic Control System

The nation's air traffic control system is the responsibility of the Federal Aviation Administration (FAA) of the Department of Transportation (DOT). It consists of an extensive network of navigation, surveillance, communication, and control facilities collectively referred to as the National Airspace System (NAS). Originally intended for use during poor weather or under conditions requiring the use of instrument flight rules (IFR), the "system," with its control features, is now mandatory for all high-altitude flights in the so-called positive controlled airspace and at major terminal areas. At intermediate and low altitudes, the system exists along defined airways Visual flight rules (VFR) operations--subject to Federal Air Regulations concerning airspace use, but not under active control of the system--are permitted outside these airways in this "mixed airspace."

All of the nation's 2,600 air carrier aircraft utilize the system, and they are at present its major user. Most fixed-wing aircraft in the military fleet -- numbering some 20,000 aircraft--fly in the system, except for training and other specialized operations. Participation in the air traffic control system varies widely among the general aviation fleet--a total of some 150,000 widely varied aircraft types utilized in many types of aviation activity including air taxi operations, executive service, flight training, recreational flights, agricultural activity, and so on.

Four primary functions of control, navigation, surveillance, and communication are interrelated in today's air traffic control system. Aircraft flying in the system must be equipped with basic electronic instruments (avionics) and are required under instrument flight rules to file a flight plan with an air traffic control facility. If "cleared" along the flight plan route, the pilot is expected to navigate himself by reference to ground-based navigational aids. The actual progress of his aircraft is monitored by a network of ground-based primary and secondary surveillance radars. The former utilize basic radar echos; the latter use a ground interrogator to elicit coded responses from beacon transponders in the aircraft (Air Traffic Control Radar Beacon System or ATCRBS). There is no ground determination of altitude; this is reported by the pilot over voice radio or transmitted automatically to the ground in an altitude-coded transponder response. Revisions of the flight plan may be requested during a flight, new clearances, based on the aircraft's progress, weather conditions, or the presence of other traffic, are communicated by controllers to the pilot. The control functions are divided between en route Air Route Traffic Control Centers (ARTCCs) and terminal towers or Terminal Radar Control (TRACON) facilities.

This system had very modest beginnings in the 1930's as an air navigation network. Its growth has been characterized by several major discernible phases or "generations." From the "first generation," which was a completely manual system based on time separations established through a process of flight progress strip postings, the system proceeded to extensive use of ground-based surveillance from primary radar and then through development of the ATCRBS. This was the "second generation," which also saw the introduction of computers to accomplish the printing of flight progress strips in en route centers. The "third generation" system, characterized by the further use of computers and terminal facilities, is now largely implemented. The semiautomated en route system now being deployed is known as National Airspace System Stage A; the improvement to the terminal area system is known as the Automated Radar Terminal System, or ARTS III.

The present functions of the ARTS III system are primarily related to the reception and decoding of identity and altitude-encoded beacon information, the tracking of beacon-equipped aircraft, and a presentation of track data with letters and numbers to identify each aircraft in conjunction with the radar and beacon information in a plan-position display. Some 61 ARTS III systems are now operational at major terminals.

The NAS Stage A system now being installed at 20 en route centers is considerably more complex. It provides for seven functions: on-line entry of proposed flight plans from both local and remote sources; automatic error and legality checking of all filed flight plans and other inputs; automatic flight plan update or revision prior to the issuance of the clearance; manual initiation of automatic processing on departing flights; automatic tracking of both beacon-equipped and nonbeacon aircraft (radar tracking); automatic flight plan updating, data forwarding, and display; and automatic track and track-control updating, data forwarding, and display.

Customers, Objectives, and Constraints

From an engineering and development point of view, customers of an improved air traffic control system consist of two major groups. First, there are the *operators* of the system Using the term rather broadly, it includes the 25,000 air traffic control specialists manning centers, towers, and flight service stations and the 10,000 FAA personnel associated with the installation and maintenance of the equipment and facilities. The second customer category is composed of the *users* of the system. These users--air carrier, military, and general aviation --are not a homogeneous group; there are well-known differences in their intended use of the airspace and in their ability to purchase and use various avionics. These widely varying viewpoints, interests, and capabilities which must be considered are a key point in the planning and development of the air traffic control system.

At the present time, the management and operation of the air traffic control system--including substantial amounts for new facilities, grants for airport development, and establishment and enforcement of aircraft and flight standards--requires a yearly expenditure of just under $2 billion and involves some 50,000 FAA employees. The trend has been for the size and cost of the FAA to increase in almost direct proportion to the amount of air traffic activity.

The air traffic control system is under continuous development, motivated by three general goals: to increase and improve performance, to improve safety, and to reduce costs.

Higher capacities, fewer and shorter delays, and improved service--including greater reliability and continuity--are obvious objectives for improved performance. It is also desirable to increase the geographical coverage of the system.

From the point of view of capacity, the situation varies geographically. Through use of radar, with its accurate and essentially continuous surveillance, separation standards over the continental U.S. have been reduced to a few miles. Broadly speaking, the en route system currently has no pressing capacity problems except at its interfaces with major terminal areas and in special situations where large volumes of airspace are temporarily denied due to bad weather conditions.

The major system capacity problems are in the terminal areas, where all flight paths converge, and on the surface of the airport itself, where the number of available runways and their occupancy times are limiting factors. Each terminal area has standard approach and departure routes which can be flown by reference to navigation aids. However, efficient handling of a large number of aircraft with differing performance characteristics requires extensive "vectoring" by ground controllers, who must meter and space aircraft to achieve maximum takeoff and landing rates.

Thus, air traffic control is more than just keeping aircraft apart; the more difficult problem is to bring them together safely with relatively small separations at the major airports. This problem of managing, organizing, and sequencing air traffic becomes a prime consideration in the review of proposals for new or improved air traffic control systems.

Three principal concerns arise in maintaining or improving safety: elimination of air-air collisions, landing or takeoff accidents, and accidents during ground operations. It is interesting to note that only a small percentage of U.S. aviation fatalities (under 5%) are associated with mid-air collisions.

The third objective is to prevent escalation of system manpower and operating costs as the number of controlled aircraft and the quality of control and safeguards increases. To achieve this will require increased controller productivity, which in turn will be possible only

with greater automation in the air traffic control system. But the expense which falls upon the owner and operator of the aircraft must also be minimized, and this goal is not always consistent with improved services and greater automation.

These objectives have to be considered against a backdrop of constraints and requirements which cannot be ignored. Two of these are the protection of the environment, including minimization of air pollution and noise, and the conservation of energy. The third is to provide the greatest possible freedom of flight and access to the airspace for all users. National policy has been to foster and encourage general aviation activity, and the likely future growth of general aviation traffic strongly affects planning for future air traffic systems. While it is not unreasonable to demand that a commercial airliner priced at $10 million to $20 million carry several hundred thousand dollars of air-traffic-control-related avionics, such a requirement would be an intolerable burden to general avaition aircraft. Thus, the need to accommodate airspace users who cannot make large investments in avionics or undertake their maintenance is a major constraint to planning for future air traffic control systems.

A fourth consideration--the concept of a "user charge" by which users of the airspace are expected to pay their fair share of the costs of the air traffic control services rendered--could seriously affect these matters. Taxes on aviation fuel and passenger tickets are used today to fund new airport and airway development, but there is no attempt to equitably recover all or part of air traffic control system operation and maintenance costs from the different users As a requirement of the Airport and Airway Development and Revenue Act of 1970, the Department of Transportation must shortly submit recommendations for revised user charges to Congress. The form or impact of these recommendations is not yet known, however, various factors indicate that they may not have a major impact on general aviation, and planning must continue to anticipate the growing needs of the general aviation community.

The basic objectives of performance, safety, and cost are not mutually exclusive. Fully satisfying any one of them generally will not satisfy --and indeed may be accomplished at the expense of--the others. For example, to obtain more performance at less cost is exceedingly difficult. Furthermore, the needs and desires of various users of the airspace are not identical--nor even entirely compatible. Air carriers prefer positive control, general aviation largely prefers a minimum of control. The problem, then, is this to design and engineer a system which represents an acceptable compromise among the varying requirements, constraints, and diverse needs and desires of the customers.

Future Requirements: "A Rather Frightening Prospect"

What is the likely pattern of future air traffic? Data of recent years reveral growing public use of commercial aircraft and increasing private and corporate ownership of aircraft for business or pleasure. Commercial

air passenger enplanements have recently grown at 8% to 9% per year and some 10,000 new general-aviation aircraft have been produced each year. The corresponding expectation is that all measures of air activity, including both en route and terminal-area traffic, will show continued substantial growth in the range of 5% to 7% per year; this means that the demand for air traffic control services will double every 10 to 15 years.

This is, frankly, a rather frightening prospect, for we can be certain that over the same general time period there will *not* be a doubling of major hub airports or the runways on these airports (in fact, little physical growth is expected with which to accommodate the increased demand), there will *not* be a doubling in the range of altitudes which aircraft desire to use, there will *not* be a doubling of major city-pairs between which the bulk of this traffic will travel, and the radio spectrum available for air traffic control use will *not* double.

In air traffic control, 10 to 15 years is just about the length of one generation or, perhaps more pertinently, just over one air traffic control development/installation cycle. That is to say, the time period required for major equipment or subsystem efforts, measured from existence of a technology or technical possibility through the stages of concept, breadboard, test, prototype, decision, procurement, installation, and check-out to a point of wide-spread field operation, can be from seven to ten years--or perhaps longer if budgets are tight or international considerations are involved. Thus, the expected doubling is in fact not very far into the future when measured in terms of system acquisition cycles.

In 1969 the Department of Transportation appointed an Air Traffic Control Advisory Committee to study this issue; its report contained the concept for an improved air traffic control system which could be achieved for the 1980s, and this concept has essentially been adopted by the FAA. This is not yet a commitment to implementation; rather, it is a commitment to those engineering and development activities necessary to investigate and evaluate such a future system.

Alternatives: The "Clean Sheet" Approach

The Air Traffic Control Advisory Committee recommended evolution and improvement of the present ground-based and beacon-based system, with priority given to the greater use of automation and the introduction of a new concept of Intermittent Positive Control (IPC). The Committee's recommendation is now referred to as the "Upgraded Third Generation System" (UG3RD), building on NAS Stage A and ARTS III, which constitute the "third generation" system.

This UG3RD system has been weighed against a "fourth generation" system, the Advanced Air Traffic Management System (AATMS), and put forth in an independent Department of Transportation study which began as a "clean

sheet" approach; that is to say, it attempted to answer the question: What would you do if you could start all over? AATMS was based on a constellation of satellites for surveillance, navigation, and communication functions. The advantages of this satellite concept include complete coverage of the airspace in a single coordinate system, capability for independent altitude measurement, and the possibility of consolidated ground control facilities. The disadvantages include high reliance on single elements and, hence, high susceptibility to their failure, vulnerability to jamming (either intentional or not), and large initial investments for both ground and airborne equipment.

"Return Air Traffic Control to the Cockpit?"

A second challenge to UG3RD came from an Aviation Advisory Committee commissioned by Congress, whose report raised the question of "distributed management"--that is, a return of air traffic control to the cockpit. Described in this fashion, the idea seems attractive, but it has never been subjected to a detailed analysis or reduced from a broad concept to a specific design. Present thinking is that this idea is more properly described as "distributed responsibility," and it is not clear that one should build air traffic control systems around a system in which responsibility is distributed rather than focused. Plans for returning air traffic control to the cockpit also present difficulties of achieving efficient traffic organization and management. In a distributed system, each aircraft cannot determine what it should do without reference to the intentions and location of many other aircraft, and to provide each aircraft with such a current data base is difficult and expensive. Airborne collection of this data is not feasible; the data would have to be collected on the ground and relayed to the using aircraft. Overall system coordination and management and the need to guard against pilot blunders or equipment malfunction probably would require parallel operation of today's ground system --although perhaps more in a monitoring than a control mode.

In sum, the transfer of air traffic control to the cockpit is not a foreseeable development, since it is unlikely to increase capacity or decrease the traffic or data processing load on the ground system in any significant manner.

Airborne capabilities could, however, provide some "coast" capability in the event of ground system failure. And there is also the possibility that certain navigation functions in terminal areas and the responsibility for station-keeping between flights along a route can be assigned to pilots in properly equipped aircraft. One possibility is the so-called Airborne Traffic Situation Display, in which a ground-derived picture is transmitted to aircraft by data link to help the pilot in terminal-area navigation and in flying closely spaced parallel approaches. This concept is being studied by means of cockpit simulation tests at M.I.T.'s Electronic Systems Laboratory. One can also look forward to greater use of sophisticated airborne systems to help

pilots adhere to flight paths furnished by a ground-based traffic management system. But the cost of the avionics for such systems probably precludes their use in all but a few air carrier or equivalent aircraft.

The conclusion of this major technology assessment effort was that systems using satellites or more distrubuted systems involving greater avionics capabilities do not seem to hold major promise over the next 20 years. The UG3RD and extensions to it can handle air traffic control requirements to the end of the century; in the meantime, experiments on satellite-based control and increased avionics capabilities will continue.

Nine Features of the Upgraded "Third Generation" System

Since the decision to proceed on its engineering and development, the Upgraded Third Generation System has been transformed into a broad system design which is highlighted by (but not restricted to) nine key features. Hardware and software development programs associated with these features have been initiated, with most test and evaluation activity acheduled for the 1976-77 period At that time, final system design choices and implementation decisions will be made, leading to initial operational capabilities in the early 1980s. The nine key features are summarized below.

1 Intermittent Positive Control. As the volume of air traffic grows in the future, the probability of collisions among noncontrolled aircraft or between controlled and noncontrolled aircraft operating in mixed airspace is expected to rise, unless other measures are taken, at a rate somewhere between the first and second power of growth in air traffic activity.

   One solution is to extend the limits of controlled airspace to include most general aviation flights, which form the bulk of noncontrolled flights. This places a heavy penalty on these aircraft (which, in terms of various measures of activity, will pass air carrier traffic by the mid-1980s), in terms of both freedom of flight and avionics requirements. Another solution, which places a heavy avionic burden on all aircraft, is to institute a mandatory airborne collision avoidance system (CAS) by which aircraft automatically exchange information with surrounding aircraft and generate collision avoidance instructions. While various CAS systems are under an expedited test program by the FAA, the solution now favored extends the current ground-based system to provide a new separation service: Intermittent Positive Control, or IPC.

   With IPC, the ground-based system will maintain surveillance on all aircraft--controlled as well as noncontrolled flights-- and will transmit advisory and collision avoidance instructions when noncontrolled aircraft approach each other or pose a danger to controlled aircraft. This service would be intermittent; it would intervene into the VFR flight regime when one aircraft's course and altitude put it into conflict with another.

Under IPC, an aircraft need not file a flight plan or operate under an air traffic control clearance. It must be equipped with a transponder to provide the ground system with its location and identity, with a capability to receive collision avoidance messages, and equipment for a cockpit display of collision avoidance information.

The ground-based IPC service is expected to be completely automatic, based on computer processing of surveillance data, detection of impending conflicts, and generation of the necessary data link messages, it is expected that *no* additions to the controller work force will be required to achieve IPC. It is also expected that the IPC can be designed to provide "backup" for possible failures in parts of the normal air traffic control system.

2. Discrete Address Beacon System. The IPC system will require an improved surveillance capability and a ground-to-air data link for rapid transmission of control messages. To be acceptable to the general aviation user, the avionics must be inexpensive.

The present beacon system--ATCRBS--sequentially interrogates sectors (slices) of airspace, and it is highly sensitive to responses to its own interrogations from other sites, and to responses from aircraft outside its own main beam. Many improvements have been implemented or are planned to correct these ATCRBS deficiencies; however, a major unresolved problem is the possibility of garbled replies from two aircraft within the interrogation beam and at the same slant-range, although separated in location and altitude. The planned solution to this problem is a method of addressing or selectively interrogating discrete aircraft. This development, the Discrete Address Beacon System (DABS) design, has been assigned to MIT's Lincoln Laboratory as system design contractor.

The objectives of DABS development are to provide the basis for the IPC function, an integral data link between ground and aircraft, and improved surveillance to make possible close-spaced air navigation routes in dense terminal areas and parallel approaches The goal is to achieve the surveillance and data link function at lowest possible cost and also to yield greater capacity, more accurate data at a higher rate, and better reliability than today's ATCRBS.

The basic design and "breadboard" verification of DABS are now complete and prototype units are being tested at the FAA's National Aviation Facilities Experiment Center (NAFEC) in Atlantic City, New Jersey. Though it uses different message formats, data rates, and modulation techniques, DABS is fully compatible with the existing ATCRBS, and an environment of mixed old and new ground sites and airborne equipment will be possible. Studies indicate that general aviation versions of DABS avionics will cost only several hundred dollars more than existing transponders.

3. Area Navigation. The existing structure of en route airways and routes within terminal areas consists of straight-line flight segments defined by radial segments of the existing VORTAC network. This limitation to radial segments has imposed extra mileage between certain terminals and has limited the number and capacity of air routes.

Advanced avionic capabilities known as "area navigation" (RNAV) now eliminate the earlier restriction to radial segments, they give aircraft the ability to follow predetermined altitude and time achedules in proceeding from one navigational fix to the next Integration and utilization of RNAV in two-, three-, and four-dimensional versions is a goal of the Upgraded Third Generation System. Such utilization will provide more routes, permitting possible traffic segregation by speed classes, etc., and separation of traffic headed for metropolitan areas served by several airports according to the airport of destination. Vectoring by ground-based controllers and pilot workloads will be reduced, and aircraft operating costs will be reduced by more direct routes and by optimum climb-out profiles.

The problems with RNAV are related less to equipment development than to proper integration of the capability into the existing ground-based system. An active study of possible features and cost benefits of area navigation capabilities is now under way, including real-time simulation of possible configurations, at NAFEC It is possible that by 1980 the en route airways structure at high altitudes and in those dense terminal areas where positive control is exercised will be almost entirely based on area navigation capabilities.

4. The Microwave Landing System. A new Microwave Landing System (MLS) is now under development to provide more flexible and precise approach and departure paths for civil and military aircraft. It will use a scanning beam or doppler technique at microwave frequencies for wide-area coverage, and it will be useful for airport guidance and also for mobile military tactical operations The system will provide a high-integrity precise signal and will be capable of installation at sites which cannot accommodate present instrument landing systems because of terrain conditions. The new MLS will make possible steeper glide paths to meet V/STOL requirements, will extend service to many airports, and will aid in noise abatement Its greater precision will also make possible close-spaced parallel approaches, thus increasing the capacity of many existing airports.

A three-phase MLS development program was launched in 1971 as a joint DOT/DOD/NASA program, with FAA taking leadership Phase I involved six contractors in techniques analysis and design definition. Phase II, completed in 1974, involved four contractors--two each on conventional and Doppler scan--in construction and

test of feasibility equipment. By the end of 1974, two contractors were selected to proceed with development of prototype equipment using the chosen scanning technique.

5 Automation. An increase in the number of aircraft to be controlled normally requires an increase in air traffic control specialists. As traffic increases, control sectors tend to become smaller and more of the controller's workload is concerned with transferring control responsibility between adjacent sectors. Introduction of automation of some functions in the air traffic control system should relieve controller workloads, increase productivity, and reduce the requirements for additional control personnel.

NAS Stage A and ARTS III represent major steps forward in the automation of air traffic control But they are only a first step. In their present form, NAS Stage A and ARTS III are primarily devoted to collecting, correlating, and presenting flight plan, radar, and beacon data; the controller must then use these data in the monitoring and control processes.

But these steps represent a base to which other functions can be added. These higher rungs of an automation ladder will include monitoring of potential problems (conflict alerts), metering and spacing of arriving traffic, and possibly the actual issuance of clearances and instructions by automatic data links.

Achieving benefits from higher levels of automation will not be an easy task. Increased automation clearly will reduce workloads, but the reduced workload may not automatically translate into increased controller productivity. There must be very high system reliability and effective backup provisions, since the confidence of controller personnel will be essential to the full acceptance and utilization of automation.

6 Airport Surface Traffic Control Growing traffic loads and new airport construction which blocks the visibility of airport facilities from many control towers results in new requirements for handling traffic on the airport surfaces. Three needs are identified improved surveillance of the airport surface, guidance information for aircraft, and improved control of the airport situation.

To improve surveillance, the current airport surface detection radar equipment is being modified and new ground surveillance radars are being developed, with a goal of achieving automatic aircraft tracking from enhance radar presentations There has also been a study of discrete sensors, such as magnetic loops placed in runway and taxiway surfaces; indeed, designs for completely automated and integrated control systems using discrete sensors at hundreds of intersections have been considered. At

the other end of the spectrum, autonomous control devices working at individual intersections are also receiving attention.

Consideration is being given to the use of ATCRBS and/or DABS for trilateration schemes (three receivers at different locations working together to pinpoint the exact location of each target by triangulation) to provide a clutter-free surface surveillance picture with aircraft identity.

The goal is a modular design for airport traffic control that can be readily adapted to individual airport situations.

7. <u>The Wake Vortex Avoidance System</u>. Trailing wake vortices especially from large aircraft on approach and landing, present hazards to aircraft following too closely behind Increased longitudinal separations (up to four and five miles behind "heavy" aircraft) provide safety but significantly reduce airport capacity.

Beyond efforts to minimize the size and effects of these vortices by aerodynamic means, the FAA is working on ground-based systems to detect and avoid these vortices. It has now been demonstrated that pulsed and doppler-radar-like devices operating at acoustical frequencies can detect and track these wake vortices, and development and testing of these devices continues on an expedited basis. Given improved knowledge of the movement and effect of vortices on aircraft, such a sensor might be the central factor in a system which would detect the presence of vortices, predict their behavior and impact, and present this information in a suitable fashion to ground controllers who can "tailor" aircraft spacings based on this information. On a longer term basis, it is planned to couple this system directly into automatic metering and spacing programs.

8. <u>Flight Service Stations</u>. The FAA currently operates a network of some 400 Flight Service Stations (FSS) at which general aviation pilots--the primary users--may obtain face-to-face or telephone weather briefings from FSS personnel and file their flight plans. This network of stations is technologically and functionally the same as it was in the 1940s, most facilities and equipment are deteriorating and obsolete, and the system is labor-intensive and unable to meet present demands for flight services.

A new automated Flight Service Station concept, developed by a joint study team of FAA and the Department of Transportation, proposes three basic elements: a central processing facility; some 30 to 50 full-time, manned key stations; and a nationwide total of some 3,500 unmanned, pilot-self-service terminals at approximately 3,500 locations. When this network is completed, virtually all pilot requests for preflight service (i.e., weather briefings and flight-plan filing) should be fulfilled through unattended, automated terminals. Pilots will use specially designed input/output devices, such as automatic printers or display tubes, to obtain and file preflight information. Flight

specialists will be available in the manned hub stations for en route communications, emergency flight assists, and system monitoring

9. Aeronautical Satellites for Transoceanic Flights. Oceanic air traffic control and air carrier communications are presently conducted over high-frequency radio circuits which are of relatively low reliability and are approaching saturation in the North Atlantic and eastern Pacific. Surveillance of the oceanic airspace is nonexistent; separation and control are based on pilots' reports of their aircraft positions as determined from on-board navigation equipment Improved communications and surveillance will be required to handle the smaller aircraft separations necessary with traffic loads forecast for the 1980s, the alternative will be lengthy ground delays or the use by some aircraft of less advantageous flight tracks.

   Various solutions have been considered over the past ten years, and now there is universal agreement on the optimum solution, the use of satellites in geostationary orbits for relaying voice and data link messages to and from transoceanic aircraft. Ranging techniques using two satellites will make possible an independent surveillance capability.

   A joint international program to test and evaluate the application of satellites to oceanic traffic control has been considered for several years. Now this program is approaching reality with an agreement between the U.S., Canada, and the European Space Research Organization (ESRO) representing nine European countries, for an AEROSAT program of two satellites over the Atlantic. Launching of these satellites is to begin in mid-1978

Compatibility Within Constraints

If the nation's air traffic control system is to respond to a predicted continuing growth of air traffic in the next 10 to 20 years, a major technological thrust must be accomplished to double system capacity. That effort is now in process, and it will lead to an "upgraded third generation" air traffic control system for the 1980s and 1990s. It will be a direct evolution from today's third generation system, and much of the new equipment will be compatible with today's hardware; existing capabilities are being extended within the current functional and system framework. Nine major developments are now under way by FAA to achieve the desired goals within constraints of cost and safety.

Airports

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Introduction

Airports serve as interfaces between the air and ground modes of an air traveler's journey. An airport can be divided into two distinct parts, the airside and the landside. The airside consists of the runways, taxiways, and aprons on which aircraft are parked. The landside is made up of the passenger and cargo buildings, parking, and vehicular circulation within the airport boundary. Outside the airport proper, there are two features which are quite important to the operation of an airport. On the airside, the terminal airspace adjacent to the airport significantly influences the capacity of the runways since capacity is dependent on regulations governing aircraft operations in the airspace. On the landside, access to the airport is an important factor that influences the capability of an airport.

The following important statements have been extracted from the Civil Aviation Research and Development Policy Study.[28]

> "The tremendous growth of the commercial airlines and the user demand for services have produced serious congestion in and around airports--Consequently, it is one of the key areas requiring concerted attention now if civil aviation is to meet the ever greater demands forecast for the future.--Eliminating congestion in the Nation's major terminals can have great social value. Congestion at metropolitan airports indicates that the full economic potential is not being attained. Reduction of congestion will aid these metropolitan areas in meeting more fully the needs of both business and the public. In addition with land becoming scarce and competition for remaining open space increasing, there is the need to utilize this resource more efficiently and intesively. Priority effort devoted to resolving the airport congestion problem offers the promise that civil aviation will be able to use existing airport land more effectively and to site new airports on fewer acres than at present. Attainment of these two goals will benefit the general public and will permit civil aviation to meet the demands of the users in the decades ahead."

The report of the Air Traffic Control Advisory Committee[29] estimates that the number of airports under restricted operations will grow 20 to 30 by 1980 and 40 to 60 by 1995 unless the terminal congestion problem is improved substantially.

Airport congestion manifests itself in varying degrees at major airports in the following areas.

1. Access/egress

2. Parking

3. Processing of passengers and their baggage

4. Aircraft gates

5. Ground control of aircraft

6. Runways

7. Terminal area air traffic management

The great difficulty in acquiring and developing new airports to relieve congestion has resulted in a concerted effort by the federal government to seek ways in which the airside capacity of existing airports can be increased. A great deal of the research now under way for increasing airside capacity through improved air traffic control procedures and aids to navigation is described in preceding section on air traffic control. Most of the requirements for hardware are included in the Upgraded Third Generation Air Traffic Control System. Suffice it to say that the largest impact on capacity will occur when the minimum longitudinal spacing between aircraft in IFR conditions can be reduced to two nautical miles. This is clearly demonstrated in the MITRE Corporation report to the FAA titled "FAA Report on Airport Capacity."[30] This reduction is a goal of the Upgraded Third Generation System.

Research and Development Work on Airports

Airside research and development work on airports began in the mid-1950s with the establishment of the Airways Modernization Board, a predecessor to the Federal Aviation Administration. Since federal concern from the standpoints of safety and funding was on the airside, most of the research and development (R&D) effort on airports was and continues to be on the airside. As a result, the airside has received much more attention than the landside which has led to the observation that landside congestion, particularly that associated with airport access, may be the limiting factor in the ability of airports to accommodate growth.

From the standpoint of the airside capacity, the highest priority items in R&D are the wake vortex and metering and spacing programs.* Unless

*Metering and spacing is a generic term which describes a composite of activities necessary to plan and regulate the rate, order, and separation of successive arriving and departing aircraft.

the wake vortex problem is solved, there can be no reduction in longitudinal spacing of aircraft. The FAA is committed to an extensive R&D program focused on the prediction of wake vortices. With reliable prediction, the probability of avoiding wake vortices is much larger, thus permitting a reduction in separation.

Two products are under development in this area, a Meteorological Advisory System and a Wake Vortex Predictive System. Observations in the field indicate that wake vortices are not encountered by aircraft during certain wind conditions. When these conditions exist, minimum aircraft separation requirements may be reduced. The Meteorological Advisory System will provide continuous monitoring of wind conditions in runway approaches to provide current data concerning whether or not wind conditions which quickly move vortices are present. The Wake Vortex Predictive System will provide a continuous and detailed forecast of vortex conditions. The system is based on vortex sensors placed in the approaches to the runway. Information from these sensors coupled with current meteorological data is used to predict the presence of vortices.[31] A parallel effort by NASA to develop a better understanding of the formation of vortices and thereby model their behavior is also under way. NASA is also studying how airframes could be altered to reduce the severity of wakes. Both these efforts (FAA and NASA) are very important and need to be pursued as rapidly as possible.

Another important factor with respect to increasing runway capacity is occupancy time. Runway occupancy time applies both to the time taken for arrival aircraft to clear the runway after touchdown and the time taken for a departure to taxi into place and proceed to lift off. The importance of runway occupancy time was recognized nearly twenty years ago when the Airways Modernization Board sponsored research to develop the geometry of so called "high-speed exit taxiways" and to determine their location.[32,33] While these exits have proven to be operationally feasible for narrow-body jets no investigation has been made to determine how feasible they are for widebody jets of the 747 type. Further, high speed exits have not been used as effectively as they might be; consequently, it is necessary to find out why this is so. Currently the FAA is developing a research proposal to ascertain more facts about exit taxiways.

High speed entrances have also been discussed as early as 1960. Their operational feasibility or savings in runway occupancy time has never been adequately demonstrated. A number of operational questions[33] must be answered before any progress in the area can take place. In the author's opinion, the advantages of high speed entrances are doubtful.[34] This is not to say that aircraft should not have ready access to the runway without requiring them to make tight turns.

Control of a number of aircraft on taxiways simultaneously moving across many intersections is now performed manually and visually. This control is a major task at very busy airports especially when the visibility is

poor. There is now an ongoing project at the Transportation Systems Center sponsored by the FAA to look into the matter of ground guidance in poor visibility. This will require improvements in surveillance, guidance, and control.

Another factor that offers a potential for increase in airside capacity is the reduction of lateral separation between parallel runways for simultaneous operations. The current standard is 4,300 feet, and it is hoped that sometime in the future this can be reduced to 2,500 feet enabling some airports to add runways on their existing properties.

A substantial effort has been made on optimizing the operations on closely spaced parallel runways (i.e., as close as 700 feet) which led to the concept of "dual-lane" runways, wherein one runway is used for arrivals and the other for departures. It is claimed that with a dual-lane runway, a 25% to 50% increase in capacity can be achieved over a single runway in instrument flight rules (IFR) conditions when the demand consists of both arrivals and departures. The gain is also substantial in visual flight rules (VFR) conditions.

In addition to the constraints on capacity already discussed, there are the environmental constraints, due to noise, pollution, and closure of airports by fog. All of these elements are receiving attention so that hopefully some day these constraints will essentially be removed or substantially reduced.

In summary, the discussion thus far has focused on potential increases in airside capacity. For the airports surveyed in Reference 30, the IFR capacity is only 60% to 80% of VFR capacity and a substantial effort must be made to increase IFR capacity. Many of the projects that deal with this problem are included in the Upgraded Third Generation System; others have been touched upon in this paper. If all of the improvements on the airside discussed were to be put into effect, the demand might be accommodated up to the late 1980s or possibly early 1990s. After that there seems to be no alternative but to build additional airports despite the fact that many voice the opinion that this will be impossible to do. Much congestion on the airside is due to overscheduling during peak hours.* This matter deserves serious study since restrictions may have to be placed on more and more airports as traffic grows** unless capacity can be increased.

Landside

As stated previously, the federal government has done very little in the way of R&D on the landside of the airport with the possible

*Overscheduling means scheduling more flights than the capacity of the airport.

**Restrictions already occur at several airports in the U.S.

exception of highway access. Many of the investigations dealing with passenger processing have been sponsored by the airlines either as in-house studies or by manufacturers of equipment (i.e., the Docutel system of baggage handling). Reference 30 indicates that demand will reach landside capacity at six of eight major airports surveyed by 1985 or earlier if nothing is done. If this is the case, landside capacity may be more limiting than airside capacity at some airports. This finding prompted the FAA to sponsor (through the Transportation Research Board) a workshop (in April of 1975)[35] to seek ways and means for improving landside capacity and corresponding levels of service. It was the sense of the workshop that capacity constraints were primarily not due to lack of R&D but were primarily due to institutional, environmental, and financial factors. Nevertheless, some of the findings are of interest and are discussed herein.

Gate delays resulting from an insufficiency of gates or an inefficient utilization of available gates add substantially to passenger and airline delay and to apron congestion. Often a single airline is experiencing gate delays and holds while other gates at nearby airlines stand idle. The practicality of mutual use of gates during busy periods should be further studied to relieve terminal gate requirements. Remote parking might well be used during peak periods of activity and particularly for charter flights.

Reference 30 points to airport access as one of the crucial elements of landside capacity and one that could inhibit the growth of an airport much more so than other elements. The survey indicates that even with plans for additional access to the major airports, many airport sponsors indicate that such expansions would not be enough to accommodate the passenger demand projected in the early 1980s. This led to a Department of Transportation ad hoc working group[36] composed of operating administrations within the Department to study this problem. Several of the major points which surfaced from this report are as follows:

1. "Evaluations of landside congestion and the interface problems have been largely subjective; lack of adequate data, lack of a validated analysis methodology, and lack of performance criteria hinder objective studies."

2. "Airport/urban interface issues must be addressed with an intermodal framework, aimed at achieving an equitable distribution of federal resources for urban and intercity transportation and assisting local agencies to develop improved transportation systems in accordance with local priorities."

3. "No new sources of federal financial assistance appear warranted at this time, in view of the opportunities to more effectively utilize existing resources and planning mechanisms."

4. "Congestion is airport-specific and occurs most frequently on highways adjacent to and inside the airport boundary; private autos account for 70 percent of all airport trips, rubber tired vehicles 95 percent."

In the short run, there is a need to examine the feasibility of modifying or adapting existing traffic management techniques for use in improving airport ground access. Techniques to be investigated include roadway television surveillance and control; changeable roadway message signs (to alert users to upcoming bottlenecks, full or closed parking facilities, etc.); reserved space for the exclusive use of buses, limousines, taxis, and trucks; ramp metering, and fringe parking lots. In the long run, there is a need to evaluate alternative transport vehicles as they relate to serving airport access needs, including demand analysis, level of service, technical feasibility, modal-split behavior, economic and financial considerations, and environmental and political barriers.

The lack of real estate within the airport boundary for expansion of passenger and cargo terminals and parking has led to the concept of "off-airport" terminals and parking facilities. This concept is not new and is being used to a very limited extent in the United States. Airline experience indicates a lack of enthusiasm for off-airport terminals both from a financial and operational point of view. However, a number of these terminals have very limited facilities (no baggage check-in facilities, no parking facilities), the possible reason for their low use. To be attractive, the off-airport terminal must offer nearly the same amenities as the facilities at the airport. Before any decisions can be made concerning off-airport terminals, it is necessary to assemble information concerning existing experience and to estimate the demand for these facilities for various levels of processing (i.e., ground transportation only, baggage handling, etc.). There is also the need to study the financial and political aspects of the problem as well as sponsorship. That is, should the federal government participate financially in off-airport terminals? How extensive a facility is required to attract customers?

Off-airport parking has developed at airports but its value in reducing the number of vehicles within the airport boundary is not known. It is desirable that studies be made of existing and planned off-airport parking operations to determine demand characteristics, transportation shuttle needs, and the financial requirements for construction and operation.

Within the airport boundary, the focal point of operations on the landside is the processing of arriving and departing passengers in the terminal building. As stated previously, most of the R&D work within the building has been sponsored by the airlines and performed by manufacturers of hardware.

Baggage handling performance has improved materially with the introduction of automated handling systems and the use of containers in aircraft.

While there are still bugs in various automated systems, on the whole, bags are delivered fairly promptly.[37] There is no doubt that the more automated systems have had catastrophic results when failures occur. Perhaps there is a need to analyze "fail-safe" mechanisms by providing a certain amount of redundancy.

At individual terminals, each airline furnishes the staff and equipment required to process baggage. It is therefore necessary to determine whether there is a duplication of service involving staff and facilities that are used only while the activity of the individual airline peaks. There is need for a feasibility study to determine the technical practicability and cost of sharing facilities particularly for airlines that are housed in the same building and the acceptability of a shared facility on the part of airlines.

For the international arriving passenger, the system of federal inspection of baggage is worthy of review to determine whether the benefits to the public provided by these inspections is commensurate with the payments required of the public. Anyone who has traveled abroad is well aware of the fact that customs procedures in Europe are far simpler than in the U.S.

For departing passengers, the airlines have investigated advances in the issuance of tickets and boarding passes.[38] Automatic ticket printing and boarding pass hardware has been installed at several airports for trial and observation. Several airlines are looking beyond just printing and processing of a magnetic ticket but are looking at the following objectives. One of these is the total elimination of the ticket coupons. An airline is studying the feasibility of using credit card readers that will accept a customer's magnetically encoded card and issue not a ticket but a boarding pass. Another airline is investigating automatic self-ticketing for a passenger who has a reservation and an applicable credit card. The ultimate goal is a "self-processing" system. With such a system, it may be possible to eliminate dedicated lounges for each departure gate, providing instead a pooled common lounge to handle a number of gates. This will encourage the installation of more sophisticated processing systems because equipment serving many gates will have considerably more use. All in all, it appears that airlines are giving attention to processing the departing passenger in a more expeditious manner. Here again, the question can be raised as to the practicability of airlines sharing these devices in order to minimize duplication of costly equipment.

Another important factor influencing the orderly flow of passengers is the passenger information system at airport terminals. While there has been considerable improvement in the last decade, continuing study is necessary to develop alternative systems for effectively communicating information to passengers as to locations of key points in the building.

One of the most frequently observed bottlenecks in airports is at the curbside of passenger buildings used for handling people, bags, and

vehicles. The complexity of the function of merging people and vehicles in addition to the randomness of people and vehicle arrivals partially explains this problem. There is a need to study this problem and to determine if any improvements can be made.

The current Airport Development Aid Program (ADAP) and the several proposals for its revision preclude the use of federal funds for landbanking for new airports or expansion of existing ones. It would be desirable to determine whether legislation to amend the present law to include landbanking is justified and whether there are statutory restrictions to do this.

In the area of cargo processing, the feasibility of off-airport facilities needs to be studied since available space at airports is becoming less and less. Much cargo is carried in the bellies of passenger aircraft. This cargo must be moved from the cargo terminal to the passenger terminal gates and then loaded on the aircraft. Since the advent of widebody jets, specialized equipment has had to be developed to load and unload cargo. As the volume of cargo increases, this entire operation requires scrutiny to determine if any bottlenecks will occur in the future.

The future impact of airport security regulations on landside capacity, congestion, and delay merits investigation.

On the airside, the government has funded studies which have led to the development of tools to determine airside capacity and delay.

The same sort of thing has not been done on the landside of the airport although parts of the landside, particularly the functions in terminal buildings, have been simulated by airlines and others. It would be desirable to launch a national effort to develop a standardized methodology for estimating landside capacity and delay.

Summary Overview

Airports are an essential part of the air transport system. In the United States, there are several airports that are nearing saturation, and many more airports will reach saturation even with moderate growth of traffic before the year 2000. Saturation results in inconvenience to passengers and shippers of goods and substantial additional costs to the airlines not to mention the large wastage in fuel consumption.

In order to prolong the time before certain airports become saturated, it is necessary to achieve a better utilization of these airports. This will require a critical examination of airline practices and procedures with respect to processing passengers and scheduling aircraft.

On the airside of the airport, the federal government has taken a leadership role in research and development related to increasing airside

capacity, but this is not the case for the landside portion of the airport. Federal support for research and development will be needed in this area. The problems are not so much technical as they are financial, institutional, environmental, political, and regulatory.

It is estimated that on the airside, with all of the innovations in air traffic management implemented, some of our major airports will be saturated by the late 1980s. On the landside, saturation may come about even earlier; so what are the alternatives? Certainly we should press on to establish how airports can be utilized more effectively; but what is the solution after this is done? There seems to be no other alternative but to build more airports despite the fact that they are quite unpopular with the public. So in the year 2000 and beyond, we will probably be using our existing airports more effectively and developing new ones.

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IV. TECHNOLOGICAL CHARACTERISTICS OF HIGH-SPEED RAIL SYSTEMS

J. C. Prokopy
Peat, Marwick, Mitchell & Co.

IV. TECHNOLOGICAL CHARACTERISTICS OF HIGH-SPEED RAIL SYSTEMS

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IV. TECHNOLOGICAL CHARACTERISTICS OF HIGH-SPEED RAIL SYSTEMS

J. C. Prokopy
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Brief Description of Physical and Operational Features

Rail systems differ from other high-speed ground transportation modes in terms of the guidance system used--the traditional flanged steel wheel on twin steel rails. Two levels of technological advancement are anticipated by the year 2000. First, Improved Passenger Train (IPT) systems utilizing advanced suspension systems and high power to weight propulsion will permit operations in the speed range of 80 to 150 mph over existing roadbeds. Secondly, truly high-speed rail (HSR) operations will approach the 250-mph design limit for rail systems on new grade separated rights-of-way with few curves or steep gradients.

Several promising alternatives exist within this broad definition, differing with respect to specific guideway configuration, vehicle design, and power and control systems. These alternative system configurations are briefly reviewed below.

Alternative High-Speed Rail System Configurations

Table IV-1 summarizes the range of promising vehicle and guideway configurations for IPT and more advanced systems. The particular subsystem configurations of the various candidate prototype systems being developed for service by the year 2000 are listed. Operational performance data are also listed for each candidate.

Operating Costs

Unlike airline operations, rail seat-mile costs do not vary widely with stage length. Most direct operating costs are considered to be a direct function of distance. Crews are generally paid by the mile, for example.

Most other direct costs are also a significant function of cruise speed. Maintenance costs of the same equipment and track may increase as much as fourfold between 80 and 120 mph. Equipment capital cost is also relatively proportional to distance since equipment cycle time consists primarily of running time. Each intermediate stop adds only about 5 minutes and corridor equipment can be turned usually in less than an hour, compared to total trip times of 2 to 6 hours in corridors, and a day or more for long distance routes. Equipment utilization depends more on the precise nature of the corridor rather than stage length. Indirect operating costs include not only terminal costs, but also costs of maintaining the guideway over which trains operate. Thus, total

Table IV-1

ALTERNATIVE SYSTEM CONFIGURATIONS

	IPT										Advanced High Speed		
	APT 250 (England)	LRC (Canada)	GMD Futura (Canada)	UA Turbo Train	ANF/Rohr RTG (France)	Metroliner	NYDOT Gas Turbine Car	JNR Shinkansen (Japan New Tokaido Line and extension)	Amtrak E60CP Metro Liner 'shell' Cars	Amtrak SDP45 Long Haul Cars	APT-400 (England)	ANF TGV (France)	JNR Shinkansen (Japan)
Rolling Stock													
Individual cars hauled by locomotive		0	0						0	0			
Individually powered cars operating in multiple						0	0	0					
Semi permanently coupled trainsets of power unit and coaches	0			0	0						0	0	
Push-pull power units at either end of non-powered coaches		0		0									0
Propulsion													
Diesel-electric		0	0							0			
Gas turbine	0			0	0		0					0	
Electric pantograph/cantenary						0		0	0				
pickup shoe/third rail													
linear induction motor/reaction rail											0		0
Suspension													
Truck springing					0	0	0	0	0	0		0	0
Tilting body (pendulum)				0							0		
Active suspension	0	0											
Operational Performance													
Number of Seats per car (C) or train (T)	400/T	84/C	NA	200 350/T		66/C	NA	900/T	66/C	70/C	400/T	34-56/C	987/T
Maximum Speed (mph)	155	120	120	160	125	160		161	120	100	250	186	310
Typical Block Speed 225 miles 5 stops (NY Washington) Upgraded Line	90	90	90	110	90	110		100	90	65	180[1]	140[1]	220[1]
Nominal Turnaround Time at End Points						1 hour all candidates							
Nominal Station Dwell Time						2 minutes all candidates							

GUIDEWAY SUPPORT OPTIONS

Crossties in ballast hardwood
concrete
steel
Concrete beams
Concrete slab

↓ increasing speed potential

SIGNAL AND CONTROL SYSTEM OPTIONS

Centralized Traffic Control (CTC) with on board control cab signals (up to 125 mph)
Fully automated operation (over 125 mph)

[1] High speed alignment assumed

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operating costs increase almost proportionally with distance, and consequently are relatively constant regardless of stage length.

Table IV-2 summarizes direct and indirect operating costs in 1974 dollars for a 350-seat train with a cruising speed of 120 mph (enabling, for example, a New York to Washington block time of 2.5 hours with 5 stops). Data for higher speed trains are not available, but operating costs should rise significantly at higher speeds. The 350-seat train size is an average--smaller than the capacity required for high density corridor operations (such as between New York and Washington), but larger than that required in other less dense corridors such as St. Louis to Chicago.

Investment Costs

Tables IV-3 and IV-4 summarize estimated capital costs for vehicles, guideways, and infrastructures for high-speed rail systems. Some costs presented come from studies conducted in 1970 and 1972, assuming 1970, 1971, 1972, and 1973 prices. Costs from these sources have been adjusted to 1974 levels by a compound inflation factor of 10% per year. Guideway and infrastructure cost estimates are extremely approximate, since actual costs are quite site specific.

Energy Requirements: 10^3Btu/Seat-Mile

	Passengers	Cruising Speed	Energy Requirements
Metroliner	382	125 mph	.63
JNR Shinkansen	987	130 mph	.95
UA Turbotrain	144	150 mph	1.05
	144	170 mph	1.30
	326	125 mph	.62
Other IPT	300	120 mph	.30
	150	150 mph	.51
	300	150 mph	.43
	600	150 mph	.36
	900	150 mph	.34
	300	170 mph	.53
	300	150 mph	.38

Source: *High Speed Ground Transportation Alternatives* (FRA-U.S.DOT, January 1973).

Table IV-2

DIRECT AND INDIRECT OPERATING COST PER SEAT-MILE
1974 Dollars
Assume: 120 MPH Cruising Speed
350-Seat Train

Direct Operating Cost	Multiple Unit Electric		Electric Loco-hauled		Turbo	
Train Supplies/ Expenses	$.0020	(6.2%)	$.0020	(6.8%)	$.0020	(5.2%)
Crew	.0143	(44.6%)	.0191	(65.0%)	.0143	(37.6%)
Energy	.0021	(6.6%)	.0011	(3.7%)	.0011	(2.9%)
Locomotive Maintenance	--	--	.0005	(1.7%)	--	--
Car Maintenance	.0061	(19.1%)	.0034	(11.6%)	.0131	(34.5%)
Annual Car Capital Cost	.0075	(23.4%)	.0025	(8.5%)	.0075	(19.7%)
Annual Locomotive Capital Cost	--	--	.0008	(2.7%)	--	--
Total	$.0320	(100.0%)	$.0294	(100.0%)	$.0380	(100.0%)

Indirect Operating Costs for High Speed Rail Systems

Maintenance of Way/Structure/Comm./Signals/Power	$.00129	(7.5%)
Station Maintenance	.00007	(0.4%)
Station Cleaning/Utilities & Station Personnel	.00302	(17.8%)
Reservations, Ticket Sales, Promotion	.00746	(43.9%)
Baggage Handling	.00007	(0.4%)
Snack Bar Food Personnel	.00056	(3.3%)
Switching	.00008	(0.5%)
Dispatching	.00016	(0.9%)
Insurance	.00200	(11.8%)
Overheads	.00230	(13.5%)
Total	$.01701	(100.0%)

Source. Current PMM&Co. study of Northeast Corridor Costs conducted for FRA-U.S. DOT.

Table IV-3

INVESTMENT COST--VEHICLES
1974 Prices

	Price
Locomotives	
Diesel, 3600HP, 6-axle, train power supply streamlined car body	$ 496,000[a]
Electric 6000HP, 6-axle	727,000[a]
LRC power unit	440,000[a]
Cars	
Metroliner "shell" for corridor	421,000[a]
Bi-level long-haul coach	475,000[b]
LRC:	
84-seat coach	220,000[c]
48-seat club car	250,000[c]
Multiple Self-Powered Units	
Metroliner - 76-seat coach	1,100,000[c]
NYDOT/GE gas turbine car NEC Second Generation	800,000[d]
Trainsets - Includes Power Unit	
Turbotrain:	
200-seat train	4,250,000[c]
250-seat train	4,500,000[c]
300-seat train	4,750,000[c]
350-seat train	5,000,000[c]
RTG 5-car trainset (276 seats)	3,000,000[a]

---

a. *Extra 2200 South*, March-April 1974, p. 3.
b. *Railway Age*, April 14, 1975, p. 56.
c. Survey to Determine Potential for Improved Rail-Advanced Vehicle Service-Work Unit II (Federal Railroad Administration [FRA] and U.S. Department of Transportation, December 1972.)
d. Current PMM&Co. study of Northeast Corridor Costs conducted for FRA-U.S.DOT.

Table IV-4

INVESTMENT COSTS--GUIDEWAY AND INFRASTRUCTURE

	1974 Cost per Double Track Line-Mile
Rebuild Existing Right-of-Way (IPT)[a]	
Right-of-way improvement	$ 2,700
Right-of-way fencing (partial)	9,000
Tie renewal	25,800
Track line and surface	6,300
Curve superelevation	2,100
Rail replacement	116,200
Crossing protection	5,900
Improve signaling	3,900
	$ 171,900
New Right-of-Way	
Right-of-way grading	$ 1,016,000[b]
Bridges (minor)	315,000[b]
Right-of-way fencing	61,000[b]
Track and support	
Wood tie/ballast[c]	280,000[d]
Concrete tie/ballast	280,000[d]
Concrete beam	586,000[e]
Concrete slab	847,000[b]
Signal/communication system: IPT	102,000[b]
Signal/communication system: HSR	218,000[b]
Power distribution: IPT	242,000[b]
Power distribution: HSR	726,000[b]
Typical guideway cost: IPT	$ 2,100,000[f]
Typical guideway cost: HSR	3,200,000[f]
Infrastructure	
Stations (cost per station)	$12,000,000-36,000,000[b]
Other (storage, service, overhaul shops--total cost for NEC)	16,000,000[b]

a. Survey to Determine Potential for Improved Rail Advanced Vehicle Service-Work Unit II (FRA-U.S.DOT, December 1972).
b. RMC Unit Cost Estimates for Improved Passenger Train and Track Levitated Vehicle Systems, June 1972.
c. Cost fluctuates widely with commodity cost of wood ties.
d. PMM&Co. estimate.
e. High Speed Rail Systems (TRW, February 1970).
f. Does not include land acquisition, major structures, tunneling, or relocations.

Noise Emission

Noise generated by rail systems can be separated into two sources, the locomotive and the train vehicles themselves. The locomotive is the primary source. The sources of noise in a diesel-electric locomotive are given below in approximate order of contribution to the overall noise level.

1. Diesel exhaust muffler
2. Diesel engine and surrounding casing, including the air intake and turbocharger (if any)
3. Cooling fans
4. Wheel and rail interaction
5. Electric generator

The primary sources of noise for train vehicles come from the interaction between the wheels and the rail, and the suspension systems. Newer passenger cars with hydraulic shock absorbers, in addition to coil springs ("prestige vehicles"), produce much lower sound levels than older cars with coil springs. The condition of the wheels and track and the use of welded track also affect the noise levels. For example, welded rails can decrease noise levels by up to 5 dBA. Typical noise levels of high-speed conventional rail systems measured at 50 feet from the vehicle are given below.

Rail System	Speed	dBA
Metroliner	107 mph	92
Turbotrain	97 mph	89
JNR Shinkansen	124 mph	87-92

Source: *High Speed Ground Transportation Alternatives* (FRA-U.S.DOT, January 1973)

Future reduction in noise levels based on use of the best vehicles now available and on potential further improvement using advanced technology have been estimated as follows:

Source	dBA Reduction by 1975	1980	1985
Locomotives	0	5	8

Source: Serendipity, Inc., *A Study of the Magnitude of Transportation Noise Generation and Potential Abatement*, U.S. DOT Report No. OST-ONA-71-7, November 1970. Vols. I, III, IV, V.

Air Pollution Emission ($lb/10^3$ hp hr)

	Unburned Hydrocarbons	Carbon Monoxide	Nitrogen Oxides	Sulfur Dioxide	Particulates
Power Plant					
Diesel IPT	2.3	3.2	3.5	3.0	1.2
Regenerative gas turbine IPT	0.7	2.5	2.2	--	--
Nonregenerative UA turbotrain	1.4	5.2	4.4	--	--
Electrified Train with the following Power Plant Configurations					
Uncontrolled (1970) fossil-fueled stations with 1% S fuel	--	--	.75	1.30	.25
High-technology controls on fossil-fueled stations (available by 1990)	--	--	.35	.13	.02
50% Nuclear (no emissions) and 50% configuration B	--	--	.18	.06	.01

Source. High-Speed Ground Transportation Alternatives (FRA-U.S.DOT, January 1973).

Safety

"The passenger death rate for train travel is among the lowest for all transportation modes. With increased speed and increased traffic on existing trackage with IPT, effort will be required to maintain this safety level. One particular problem will be grade-crossing safety requiring automatic protection, including timing controls to provide for the variance between freight and passenger speeds when separate operations are not possible, and where grade separation is not economically feasible. In addition, the present problems of track and switch degradation with heavy freight service will continue to exist. Vandalism, foreign obstacles, and people on the tracks may be alleviated by fencing. Signal system improvements may be necessary to handle the increased traffic.

"Many of the foreseeable safety problems with a HSR system will be alleviated with the dedicated guideway. The excellent safety record of the Japanese New Tokaido Line (over 400,000,000 passengers without a fatality) operating on a dedicated right-of-way, illustrates that an isolated and protected system can overcome the potential hazards of increasing speeds. Foreign obstacles on the guideway could remain a problem for HSR, depending on the vehicle/guideway configuration. Security isolation of the guideway (elevation, fencing) can be traded off against the development of an automatic foreign obstacle detection system."*

Comfort

IPT and more advanced rail systems offer the passenger a ride comparable to current air operations. Discomfort arises from track roughness (vertical, lateral, and roll motion), track curvature (vertical and lateral sustained acceleration), wind gusts, and fore and aft acceleration during starting and braking. The IPT candidates utilize a sophisticated suspension to compensate for track roughness and curvature, and the more advanced rail systems supplement the improved suspension with a well maintained, heavy-duty track structure built to high tolerances, with only slight curvature and gradients.

Seating in high-speed rail vehicles compares with that in first class cabins in conventional-body aircraft, with wide seats in a two-and-two arrangement. Meals can be served at seats, but passengers are also free to move to lounge or snack-bar areas. Wide cabins permit generous aisles, and toilet and telephone facilities can be located in each car.

**High Speed Ground Transportation Alternatives* (FRA-U.S.DOT, January 1973).

Development Status

Because of funding constraints, there is currently little high-speed research and development under way in the United States. Research is limited to refinement of state-of-the-art systems and subsystems. The U.S. R&D effort has no announced speed goals. U.S. and foreign disappointment with more advanced systems such as air cushion or magnetic suspension has shifted attention back toward upgrading more conventional systems and routes. Still, many subsystems developed in advanced system R&D, such as linear induction motors, power collection techniques, active suspension, etc., can be applied to high-speed rail systems. Current foreign research programs are more extensive than U. S. programs, with active commitment to high-speed rail research in Japan, England, Germany, France, and Italy. Some research is being done by the Federal Railroad Administration at the Pueblo Test Center, including testing of foreign vehicles such as the Canadian LRC, and the Train/ Track Dynamics Lab jointly operated with the Association of American Railroads.

Special Institutional Problems

- Lack of adequate funding commitment for HSR by Administration.
- Adverse public reaction to proposed new rights-of-way for high-speed operation which cannot be diverted away from developed areas because of curvature/gradient requirements (e.g., Los Angeles TACV, Dulles Airport access system, Paris region TACV).
- Conflict between use of existing rights-of-way for passenger and freight services.

V. HIGH-SPEED GROUND TRANSPORTATION TRACKED LEVITATED VEHICLES

Frank Chilton, Ph.D
Science Applications, Inc.

V HIGH-SPEED GROUND TRANSPORTATION
TRACKED LEVITATED VEHICLES

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V. HIGH-SPEED GROUND TRANSPORTATION: TRACKED LEVITATED VEHICLES

Frank Chilton, Ph D.
Science Applications, Inc

Introduction

The tracked levitated vehicle (TLV) for high-speed ground transportation has two major suspension possibilities: the tracked air cushion vehicle (TACV) and the magnetic levitation vehicle (MAGLEV). These are noncontact suspension methods designed to permit speeds up to approximately 500 kilometers/hour (km/hr) for the TACV and speeds up to 1,000 km/hr for one variant of MAGLEV

Although the vehicles can also operate at low speeds, there is little cost benefit in doing so, except in the necessarily low-speed portion of high-speed ground transportation systems such as stations and some types of switching In fact, since wheels work well up to about 200 km/hr, TLV system designs could use wheels below, say, 100 km/hr analogous to the wheels used in aircraft landing gear.

The guideway for a high-speed ground transportation TLV system must be a special guideway with protected right-of-way and no grade crossings due to the high speed and the inability to stop within limits of reasonable acceleration for the passengers after human visual detection of objects on the guideway. Further, the guideway must be protected from the possibility of malicious mischief, such as objects on the guideway or thrown rocks, because such objects in the frame of reference of the vehicle are traveling at several hundred kilometers per hour and would easily penetrate and could do horrendous damage. Thus, the right-of-way restrictions are more stringent than for a railroad, although because the vehicles are lighter in weight (similar to aircraft), it is easy to use elevated guideways of lighter construction than for conventional railroads. Therefore, new options are possible for guideway locations such as down the center of existing freeways.

The guideway construction requirements are somewhat more stringent in that the acceleration to the passengers has to be limited in going around curves, so that the guideway would need to be banked and the radii of curvature restricted to be larger than some minimum amount, depending upon the speed of operation.

The guideways for TLVs require lateral alignment criteria comparable to the vertical alignment criteria for airport runways, in order to minimize the lateral acceleration transmitted through the suspension to the passengers or, conversely, to minimize difficult requirements upon the suspension, which would make the system unreasonably costly. There is a trade-off here because the guideway cost is 60% to 90% of the investment cost of the entire system.

Propulsion can be provided either from on-board turbofans, or turbo-generators which operate linear induction motors, or, preferable from the standpoint of noise and pollution, by the wayside pickup of electrical power. However, since that power represents 10 to 30 megawatts, there are still (1) uncertainties about the technical feasibility of the reliable pickup of such large amounts of power at several hundred kilometers per hour without unreasonable wear, and (2) some questions on safety for some TLV concepts during temporary power failures

The principal advantage of the TLV concept is its ability to handle extremely high demand compared to aircraft at approximately the same cost and comparable or better point-to-point travel time for short to moderate ranges However, TLV systems clearly require a large demand if they are to be justified by cost alone, primarily due to the cost of guideway construction.

The three types of noncontact tracked levitated vehicle are the tracked air cushion vehicle, repulsion MAGLEV, and attraction MAGLEV. Although the MAGLEV concept was demonstrated at the 1912 World's Fair, it lay dormant for many years due to there being no interest in high-speed ground transportation systems. In the meantime, the tremendous aerospace capabilities of the United States and other nations, as well as military and civilian interest in hovercraft-type all-terrain air cushion vehicles, led to a somewhat earlier exploration of this technology during the 1960s, even though the TACV is much more complicated in many respects than MAGLEV. The TACV will be described first because its technical feasibility has been demonstrated more thoroughly than that of MAGLEV vehicles.[1,2]

Tracked Air Cushion Vehicles

The principle of the tracked air cushion vehicle involves pumping air underneath the vehicle and confining it with a skirt or plenum so that it provides a flexible cushion of air as the vehicle suspension. The plenum is made of rubber and must flex or it will be destroyed, with subsequent loss of suspension when it contacts the guideway. The all-terrain hovercraft air cushion vehicles require excessive lift power in exchange for their all-terrain capability and essentially function as a special type of low flying helicopter The TACV uses the skirt or plenum to confine the air quite close to the guideway so that the height of suspension between the plenum and the guideway is on the order of one or two centimeters. The vehicles suspension height is much larger. Figure V-1 illustrates TACV designs.[3]

In order to obtain the necessary lateral guidance, the plenum must either be relatively complicated in shape, which would also imply more wear, or the TACV needs auxiliary, smaller air-cushion ducts and plenums oriented horizontally for guidance.

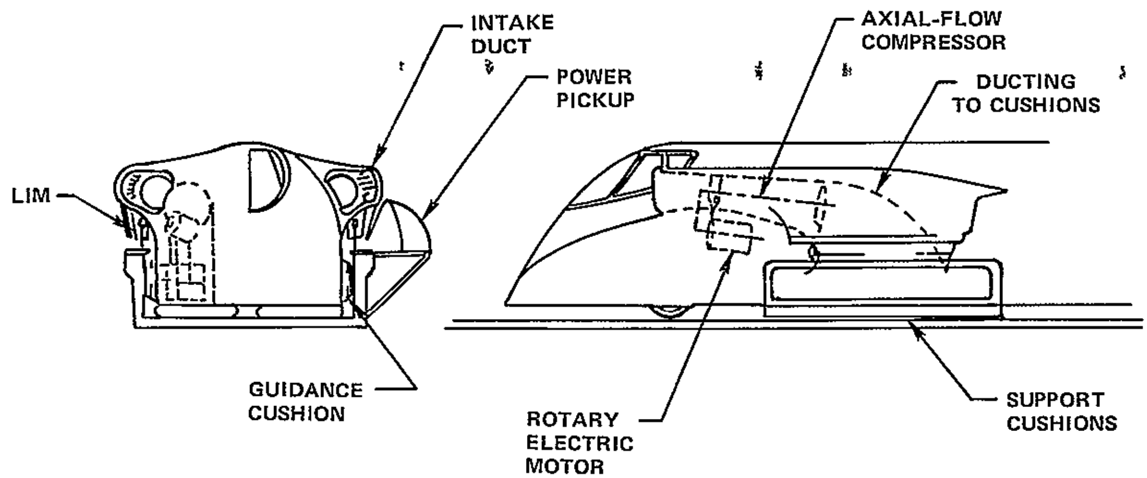


Figure V-1 TACV COMPONENT LOCATIONS

In designing the vehicle, considerable space must be allocated to the ducts that carry the air from the fans into the plenum. This space is not all wasted, however, because studies of TACV dynamics suggest that the air cushion suspension is rather "hard" due to the rapid increase in force as the air gap between plenum and guideway decreases, so that there would probably be a need for a secondary suspension which can be put in between the space allocated for the air ducts. The purpose of the secondary suspension is to give superior ride qualities to the TACV compared to what it might be without the secondary suspension (unacceptable).

In addition to the fan-pumped air, at high speeds ram air can be used in the suspension This ram air would be an additional source of drag and would increase the propulsion requirements but would decrease the suspension requirements, so there is a possible trade-off. With a guideway which has a lip, suspension could be by ram air alone.

The presence of the plenum and the necessity of providing space for the air ducts makes the frontal area of the TACV larger than that of streamlined railroad cars or of MAGLEV vehicles, and thus increases the air drag, the dominant source of dissipation of propulsion energy at high speed. Thus, TACVs are limited to approximately 500 km/hr as an economical maximum, whereas the upper limit for the repulsion MAGLEV for comparable energy requirements is more like 1,000 km/hr. For the attraction MAGLEV, the limit is not yet known since the limitation is not so much power requirements as safe performance of the control system

Magnetic Levitation Vehicles (Repulsion)

In the repulsion form of magnetic levitation, the suspension system for the MAGLEV vehicle is the magnetic field induced in the conducting guideway (usually made of aluminum) by the moving magnets located in the vehicle. Using superconducting magnets, clearances of 15 to 30 centimeters are easy to obtain, which will apparently remove one requirement for a secondary suspension. The MAGLEV vehicle frontal area size, energy requirements, noise, etc., are less than for a TACV. The use of superconducting magnets also permits the vehicle to be designed in an unbroken streamline fashion in contrast to the other two TLV concepts and, thus, to have a lower drag coefficient. Figure V-2 illustrates this MAGLEV concept.[4]

With repulsion MAGLEV, a decrease in clearance increases the lift force restoring the original vehicle/guideway clearance. The system is therefore basically stable. TACV is similarly stable, while attraction MAGLEV is unstable and requires fulltime active controls to maintain the clearance.

The advantage of using superconducting magnets is the larger clearances and, thus, a softer suspension. The lift of the magnets is proportional to the (field squared) or equivalently to the (current squared) in the magnet. Either four or six magnets would be located on the vehicle similar to wheel positions The lift and drag for MAGLEV vehicles is shown in Figure V-3. Low-speed lift would be provided by a conventional wheel system, the MAGLEV vehicle gently settling down on its wheels at low speeds or unloading as the speed increases. If desired, the aluminum could be left out of the station areas since the lift-to-drag ratio is poor at low speeds anyway. Alternatively, coils with the proper high inductance could be installed to allow lift-off at a lower speed when leaving stations, and the high drag at low speed could be used for added braking when entering stations. Leaving out the aluminum seems like the simplest and most expedient alternative since the speeds of lift-off are well within the range for rubber-tire wheel performance, and in any event, the wheels are desired as an additional safety feature in case of power failure. Braking can be performed by the linear induction or linear synchronous motor

In case of accident, the superconducting magnets hold their currents for the order of minutes giving adequate time for the vehicle to slow down gently onto its wheels. The superconducting magnets would be operated in the continuous current mode, and once energized, would continue to retain that current as long as kept cool. Such a loss of suspension is not expected without a disastrous accident which pierces the vehicle in such a way as to also pierce the magnet dewars (the cryogenic enclosures containing liquid helium).

On-board refrigeration is the preferred mode for keeping the magnets cold in order to minimize manpower requirements It is also possible to make cryogenic containers that could have hold times of two or three

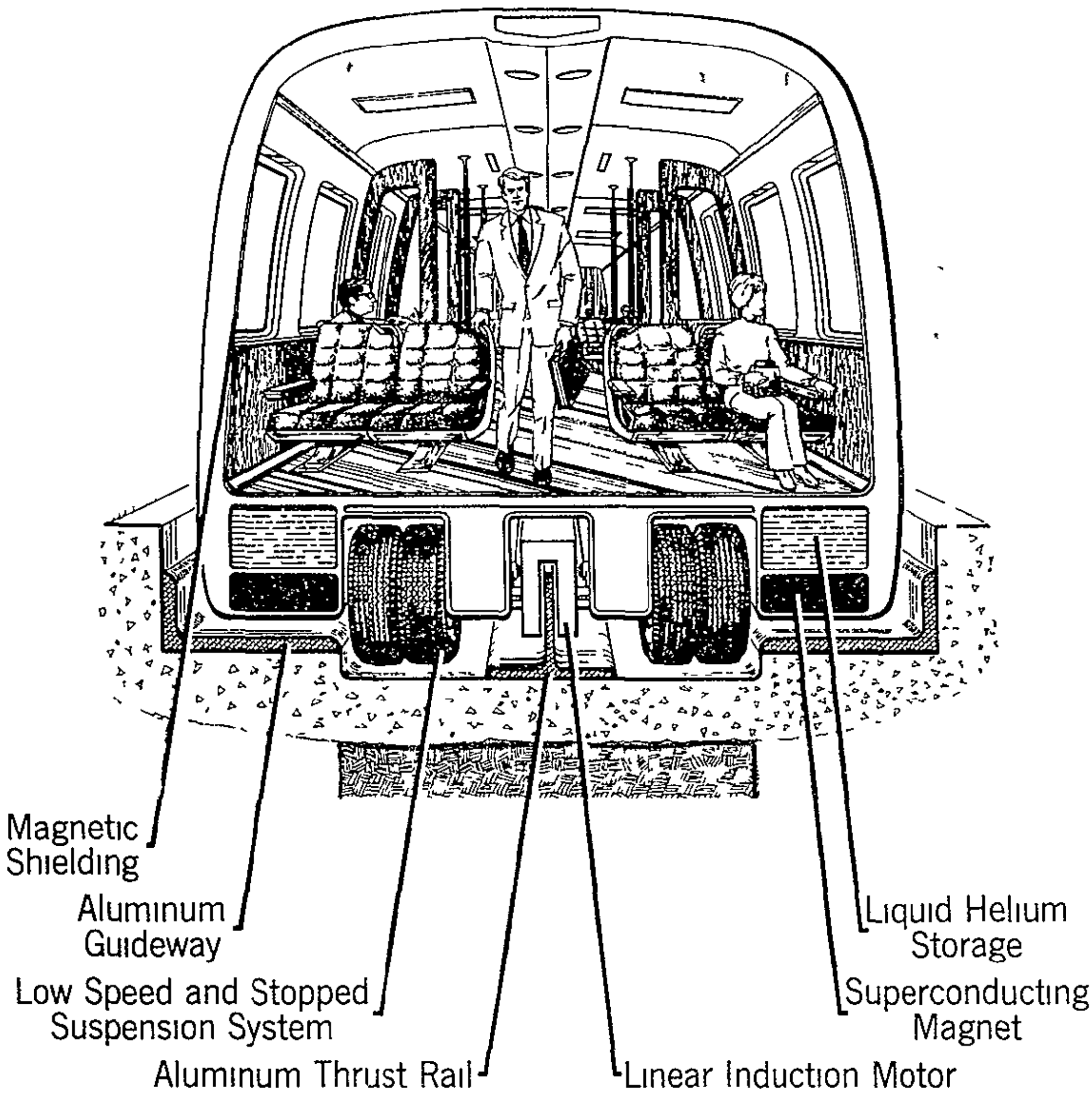


Figure V-2. STANFORD RESEARCH INSTITUTE MAGLEV VEHICLE

days and thus be topped with liquid helium either every few days, or each night, as appropriate There is a cost benefit trade-off between having a large central refrigerator, using manpower to refill each vehicle and having small refrigerators on each vehicle which are relatively more expensive in equipment cost, but actually less expensive than manpower for continuing operation.

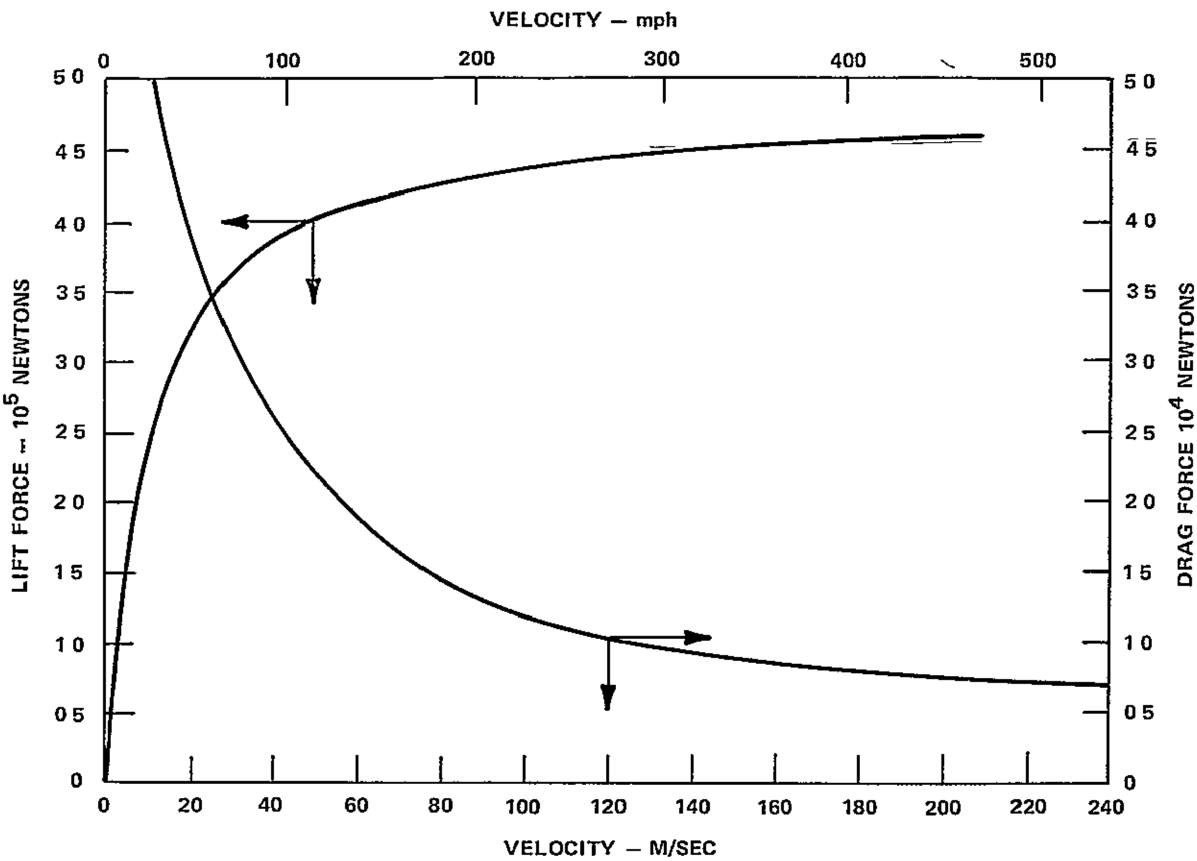


Figure V-3. ELECTROMAGNETIC LIFT AND DRAG FORCES ON A 100,000-POUND VEHICLE SUPPORTED BY SIX 2.0 x 0.5-m MAGNETS OVER A 0.02-m THICK ALUMINUM GUIDEWAY

From the electromagetic lift-and-drag curves, it is apparent that repulsion MAGLEV improves as the speed increases (with the exception of air drag) so that speeds up to 800 km/hr or 1,000 km/hr would be possible without unreasonable energy requirements, as shown in Figure V-4. Of course, this would put additional constraints on the guideway construction such as lengthening the radii of curvature and requiring a superior quality of flatness in the guideway roughness power spectral density. Figure V-5 shows a Philco-Ford concept of MAGLEV repulsion vehicles, which have on-board power.[5] From a practical point of view, the little money saved by having on-board power in the vehicles and no electrified guideway hardly compensates for the turbofan engines and their subsequent noise, pollution, and use of fossil fuel. The advantages of MAGLEV are in an all-electric silent mode, using nuclear-generated electricity, an environmentally desirable and fossil-energy-conserving

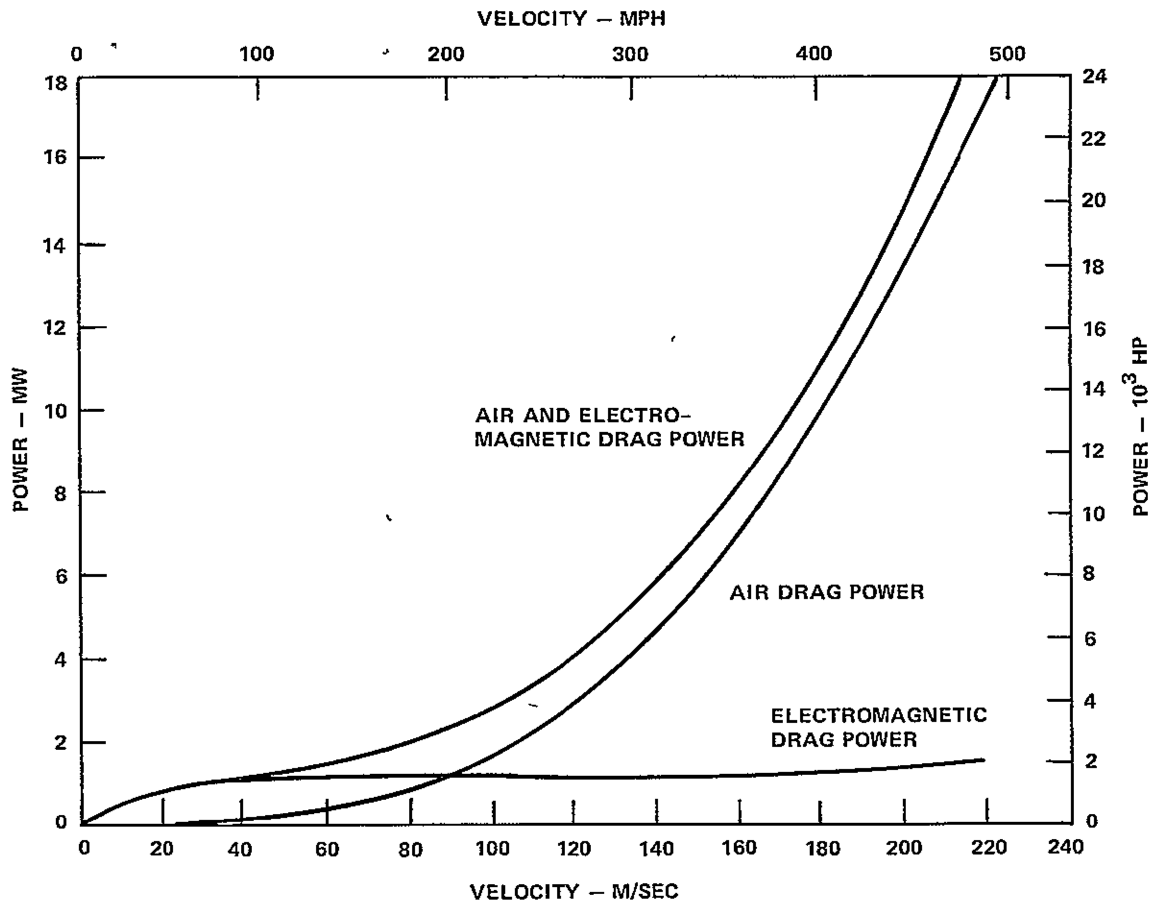


Figure V-4 POWER REQUIRED TO OVERCOME THE ELECTROMAGNETIC AND AERODYNAMIC DRAG FORCES (Aerodynamic forces are based on a 150-ft^2 frontal area and an aerodynamic drag coefficient of 0.2.)

configuration. Since the major cost is guideway construction, saving a small fraction of the cost by carrying fuel on the vehicles appears hardly worthwhile, unless wayside power-pickup at such speeds is not feasible. In that case, the synchronous guideway propulsion concept would be worth investigating, even though it is regarded as the most expensive of the three possibilities, because it would maintain the low noise, low local pollution character of MAGLEV.

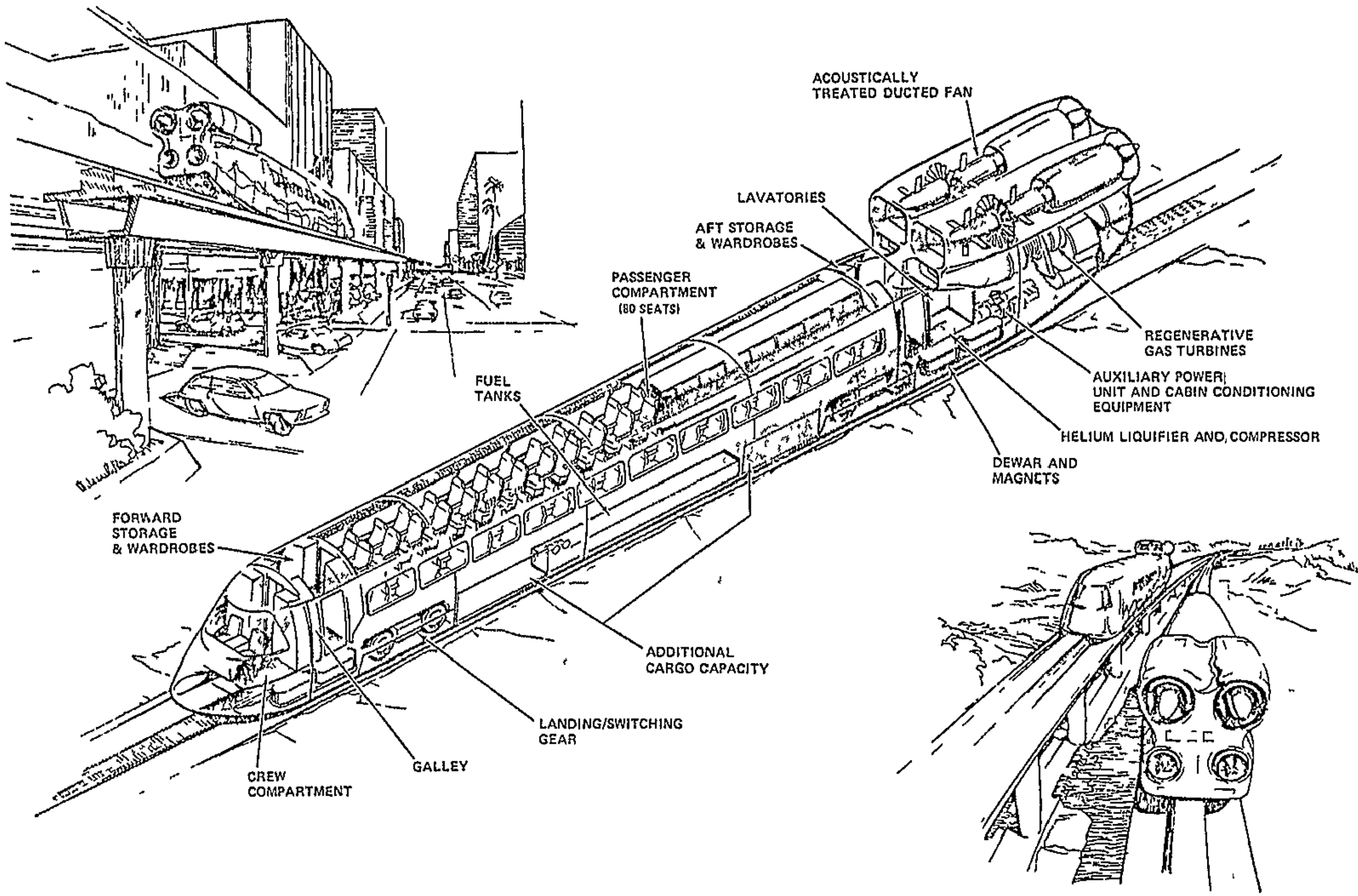


Figure V-5 MAGLEV REVENUE VEHICLE SYSTEM/BASELINE CONFIGURATION

Magnetic Levitation Vehicles (Attraction)

Although it has been well known for fifty years that an attraction magnetic levitation system could be built with conventional electric motor technology (i.e., conductor-wound iron magnet) and steel guideways where the vehicle would be pulled up toward the guideway by the magnetic field rather than pushed up from below, the concept had been discarded for reasons of control system performance until Messerschmidt-Boelkow-Blohm (MBB) and Kraus-Maffei (KM), Germany's major aerospace firms built two test vehicles in 1971. Although the development was somewhat behind repulsion MAGLEV, the attraction MAGLEV concept rapidly caught up to the demonstration stage because the attraction technology is already conventional and developed with the exception of the control system, whereas the repulsion MAGLEV system required some technological development on the superconducting magnets.

People interested in high-speed ground transportation had generally discarded this concept until MBB and KM demonstrated it, due to its intrinsic instability and the requirement of very small clearances on the order of 1 centimeter. It was expected that control problems were too difficult since maintaining a ±0.1-centimeter clearance tolerance for vehicles traveling at 400 km/hr (the minimum speed of interest for new high-speed ground transportation systems) would be prohibitive.

This control system question is still not answered, although the basic conept of attraction MAGLEV has been demonstrated. With the very small 1-centimeter clearances, the power required for suspension is relatively small, and high lift-to-drag ratios can be obtained by using laminated rail in the guideway even at the high speeds desired. The lift-to-drag ratio of attraction MAGLEV decreases as the speed increases. In attraction MAGLEV, the magnets must be out like wings in order to be within a centimeter of the rail. Long rectangular magnets work best, and in order to maintain that 1-centimeter clearance throughout the vehicle, the vehicle essentially has to be lined with magnets. Typical design numbers would be 16 magnets controlled by an on-board computer network. It is not now known what the ultimate speed of attraction MAGLEV will be. That depends on the control network and the guideway quality.

The ability of the control network to respond and keep the 1-centimeter clearance in all of the magnets of the vehicle is a stringent requirement. First, the guideway has to be aligned within a tolerance which is better than the best roadway made; however, that is possible since the laminated rail (and only a few laminations are necessary for improving the lift-to-drag ratio) can be shimmed and realigned as needed, for example with a laser beam. The problem is that alignment takes manpower of a medium-skilled level, since the steel rails must support the full weight of the vehicle, it would be expected to get out of alignment frequently, probably not as bad as, but similar to, the conventional rail alignment problem. For attraction MAGLEV a 1-millimeter displacement is serious so that the alignment criteria are more stringent; the way that this would limit speeds or contribute to unreasonable

operating cost, if the speed limit were pushed, has not been fully estimated.

Probably the most indicative description of the state-of-the-art for attraction MAGLEV is the implicit meaning of the quiet cancellation of the Toronto contract for such a system by Krauss-Maffei and the return of the funds Although the full reasons are not apparent at this time, it is evident that the control systems and the backup safety features for a power failure, in which event the vehicle simply falls, are not regarded as adequate yet for high speeds. It is really not known what the limit of this technology is. It is also apparent, though, that MAGLEV has little value at low speed since wheels work fine. All the demonstrations so far have been at speeds below 150 km/hr.

Other Tracked Levitated Vehicle Variations

There are a number of hybrid concepts which have some merit because they take advantage of the high-speed motion of the vehicle and, thus, may contribute usefully to optimization of tracked levitated vehicles.[6]

One possibility is to use ram air, in which an air scoop on the vehicle collects air and deflects it downward in order to provide additional lift Naturally, this additional lift shows up as an added component to the drag, i.e., the ram drag. Ram air can be used with each of the TLV concepts. TACV, MAGLEV repulsion, and MAGLEV attraction. However, it is regarded as most useful for the TACV with the ram air to simply be added to the suspension air provided by the turbofans, because the plenum would use it more efficiently than the proportionately larger clearances between the bottom of the vehicle and the guideway for MAGLEV.

Another variation is the ram-air jet in which a special guideway with inward lips replaces the use of a plenum in order to essentially trap the air when the vehicle is moving. Since there is no plenum, this concept applies equally well to each of the three TLV vehicle designs. The ram-air jet would reduce suspension requirements especially for the TACV and attraction MAGLEV at high speed where suspension is more of a problem for these two concepts. It is compatible with, but would appear to have little obvious advantage for, repulsion MAGLEV since the clearances are already high and since the guideway construction costs (the largest single cost by far for TLVs) would be increased by using the ram-air jet.

Guideways For Tracked Levitated Vehicles

The basic guideway possibilities for tracked levitated vehicles were enumerated some years ago. They include the U, hat, V, and circular guideway designs as the major possibilities. See Figure V-6 for some examples of guideway designs.

From an economic standpoint, these guideways are practically equal since the guideway substructure is the main cost component. The leading candidates for repulsion MAGLEV are the hat and the U guideway, for the TACV, the U guideway; and for attraction MAGLEV, its version of the U guideway with the flat bottom and vertically supported suspension rails.

Since the vehicles are traveling at 500 to 1,000 km/hr, the guideway must be protected. If it is at-grade, (1) it must be fenced since a rock thrown at the vehicle or debris on the track would be dangerous, and (2) no crossings could be allowed for automobiles since the warning time for the automobiles and the stopping time for the vehicle will normally not permit either the automobiles or the TLV to be seen by each other in time to stop a collision. Although in principle it would be possible to have grade crossings, it is regarded as highly undesirable from a safety standpoint. Protection of the TLV is probably best accomplished by having an elevated guideway for most of its length, although this is more expensive. An elevated guideway substantially reduces problems of malicious mischief, questions of grade crossings, having to build new overpasses for automobiles across the line, and choice of fences.

Since the guideway alignment and radii of curvature must be controlled for high-speed vehicles to avoid passenger discomfort due to unacceptable accelerations, there may be virtue in the elevated guideway, in that it makes the alignment problem somewhat simpler and there is less concern about settling. It might be necessary to provide for periodic guideway maintenance in order to keep the smoothness power spectral density of the guideway suitable for ride quality. This is the analog of the track alignment problem experienced by the Japanese National Railway on their express Tokkaido Line but would never be as severe for a TLV. Indeed, this is one of the reasons the Japanese have chosen the repulsion MAGLEV design for their next line. Because the forces are more spread out in the TLV than in wheel systems at high speed, the kind of maintenance required is less than, but similar to, the type of maintenance used on highways.

No new techniques are needed for guideway construction as compared with guideway construction methods that have already been used for elevated lines in projects such as BART The main problem is simply the costs of the guideway for intercity lines.

The guideways for the three TLVs cost approximately the same, or at least there are trade-offs which can result in their costing the same. For example, the smoothness of the guideway for the TACV has to be somewhat higher than that of the MAGLEV vehicle. However, the repulsion MAGLEV requires aluminum sheets or coils, and the attraction MAGLEV requires vertically supported steel rails which must be carefully aligned during installation to tolerances on the order of 1 millimeter in 100 meters.

The essential criteria for choosing among these concepts are twofold: stability of ride and cost. For example, the circular guideway has the advantage of being self-banking on curves regardless of the speed of the vehicle; however, it results in terribly unacceptable transverse oscillations, without difficult effort in the design of the guideways to provide lateral stabilizing forces. Naturally, these steps would be more expensive The other guideway designs are approximately equal as far as stability is concerned, although the hat guideway introduces complications for tracked air cushion vehicles because of the need to either have a double plenum or to carefully design a split in the plenum in order to have proper lateral stabilizing forces. The hat guideway is probably best for repulsion MAGLEV since it (1) could decrease the amount of the aluminum, and (2) admits prefabricated box beam construction easily. In attraction MAGLEV, there would be no advantage to the hat, or in fact, any particular guideway substructure, other than the necessity to provide a place to come down in case of power failure, since the lift and propulsion are provided with laminated rails above the magnets

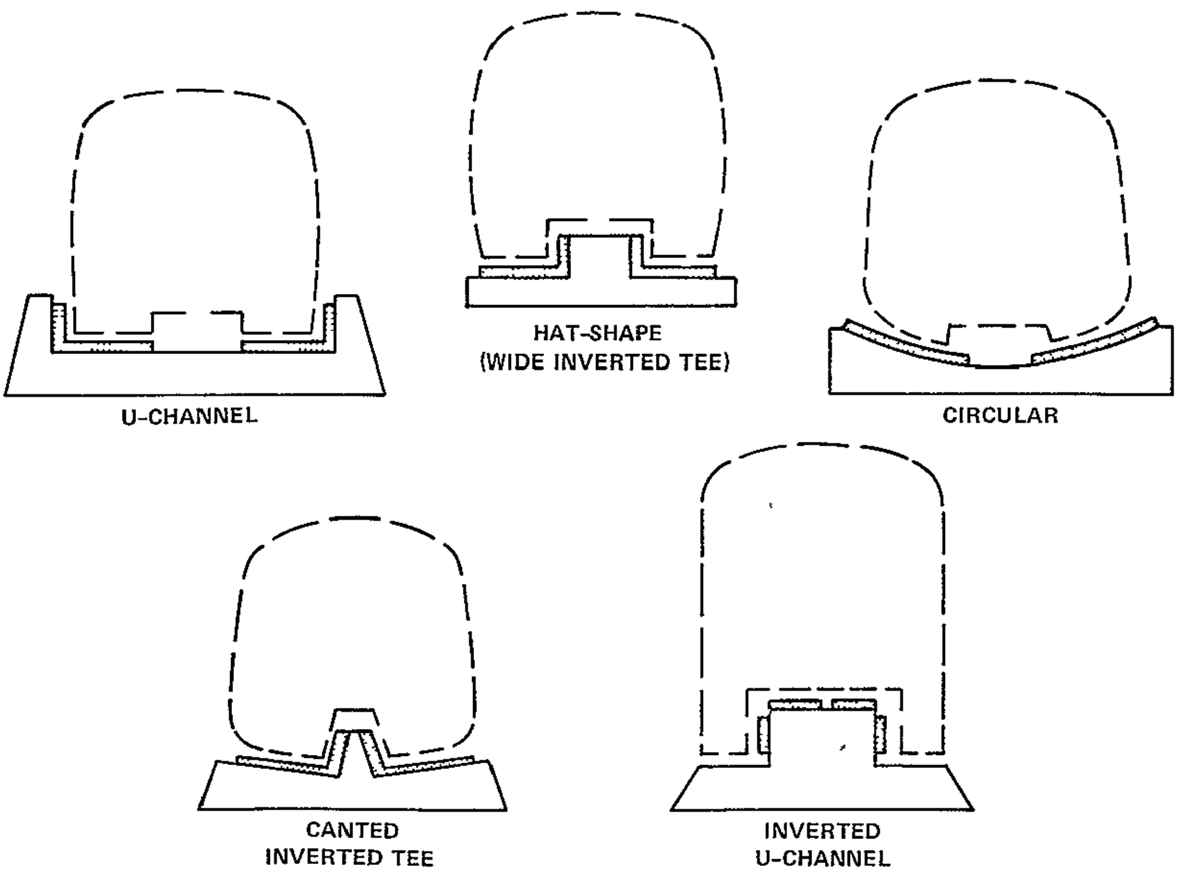


Figure V-6. CANDIDATE GUIDEWAY CONFIGURATIONS

However, the substructure for attraction MAGLEV is needed only for safety purposes, and in repulsion MAGLEV, the substructure is there only to hold the aluminum sheets or coils There are ways to either physically or electromagnetically shim misalignments in the aluminum plates or coils and simple electromagnetic means of measuring the degree of alignment or misalignment for both the attraction and repulsion MAGLEV These special adjustments for each TLV concept cost some small fraction of a million dollars per kilometer, whereas the total guideway minimum cost is several million dollars per kilometer; so the special features intrinsic to each type of TLV are not regarded as a problem.

Terminals for Tracked Levitated Vehicles

Terminal design for TLVs will differ little from those for new intercity lines such as BART, or the new terminals built for the Metroliner. The emphasis will be on providing an adequate, inexpensive terminal which needs to handle only two lines, one running in each direction. A minimum of space is required for waiting, since there will not be a large number of tracks as in Grand Central Station. The emphasis will be on pleasant, clean terminals which are functional and require a minimum of people for operation and maintenance.

Probably the choice will be made that TLV lines will primarily be elevated, so the terminals will mostly be types suitable for elevated lines. This does not make much difference in the cost of the terminal but does simplify some of the design considerations. Also, a two-story structure easily provides waiting and concession space.

Terminals will differ in the technical details of the guideway for the different types of TLV. Unless turbofan drive were chosen for the TLVs, an undesirable choice from the standpoint of noise, there would be electrified power rails beside the guideway. These would be not unlike the "third rail" of subway systems, although they would be presumably located for safety and minimized cost on the interior side of the guideway between the two lines. Since high-speed power pickup is problematic enough due to oscillations of the pickup arm (jitter), the power rail may be more complicated than a simple rail and could be as complicated as a three-rail system enclosed in a roughly semicircular housing. The two sets of power rails for the lines in each direction could be back-to-back with a common feed.

Control Systems for Tracked Levitated Vehicles

The major control problem results from the simple fact that the TLV is intended for high-speed ground transportation and passenger comfort is limited to .1g acceleration for ordinary braking and acceleration to speed, and at most, .2g for emergencies. This implies that the control system must be capable of detecting a stalled vehicle or obstacle on the guideway at distances farther than can be seen with the human eye.

Objects on the guideway are particularly serious for the TACV in which the vehicle body is well above the guideway but the plenum must have small clearances of one centimeter or so. An object of any size at high speed would tear a large hole in the plenum and rebound, hitting the vehicle underneath. That is why it is a critical problem to prevent any possibility of malicious mischief such as throwing rocks at the vehicle or onto the guideway, or placing objects on the guideway.

The Metroliner has had considerable experience in what happens if the right-of-way is not protected. When riding with the engineer, the author has personally seen objects on the Metroliner's rails at the rate of about four per hour Usually they were small coins or rocks, however, in one case it was a piece of concrete large enough to cause derailment. Fortunately, the little boys who did it (and the author) did not realize the vibration of the rails by the oncoming train would jiggle the rock off. The author wondered why the engineer was so calm. However, bigger boys could figure out a way to support that rock so it could not jiggle off. The Metroliner has also had to confront refrigerators left on the rails, and occasionally even an abandoned automobile. There have also been problems with rocks hung from overpasses at the position over the engineer's window, stones thrown from overpasses and the old favorite of suspending a tire from the overpass so that it is hit by the upper portion of the train and is bounced forward a considerable distance. In addition, old tires and rocks are often thrown or dropped onto the Metroliner. This is a dramatic illustration of why, for safety reasons, the right-of-way must be fully protected from such mischief. Incidentally, the Japanese National Railway (JNR) does not have problems that are even vaguely comparable to this magnitude. The JNR does usually fence the right-of-way.

Although proper fencing and screens can rather inexpensively take care of simple malicious mischief, the control system must be suitable for handling slowed or stalled vehicles and acts of vandalism or sabotage. Therefore, it must be able to detect objects on the guideway up to several kilometers ahead. The size and nature of objects that the control system needs to detect differ somewhat for the different systems of TLV, for TACV, a small rock is enough. For repulsion MAGLEV, only objects greater than approximately 15 centimeters are of consequence. For attraction MAGLEV, the clearance above the substructure of the guideway can be high enough so that it can also easily have a 15 centimeter tolerance limit It should probably be not much more than that since attraction MAGLEV has the control and safety problem of falling upon power failure, so that the distance of the fall upon the wheels or skids should be no more than necessary to give a little leeway for objects or ice and snow.

Information concerning the location of vehicles can be acquired by magnetic means quite naturally for both the MAGLEV systems and also magnetic means using appropriate permanent magnets or a small electromagnet for TACV systems with signal pickup lines on the guideway.

Since the headways will be in minutes, wayside detectors could be placed approximately every kilometer to signal the location of vehicles to the central control system. A vehicle stopping in a given sector would then be apparent.

Presumably, computer control would be used in order to keep track of the location of all vehicles and perform other relevant bookkeeping functions. The computer control problems would be similar to those that have already been successfully solved by the Lindenwood Line in New Jersey and are currently being solved by BART. The control problem is simpler than it would be for high density air traffic control.

The problem of detecting foreign objects on the guideway at distances far enough to do something about it is somewhat difficult. Technologies exist to perform the function, such as the use of lasers, the reflections from which can be detected by a narrow band detector sensitive to that wavelength so that the object detection system will function equally well both day and night. Microwave radar pointed forward could also be used.

Thus, it is a reasonable conclusion that adequate control systems for TLV networks would certainly be available by the time that a specific system could be chosen and the guideway constructed. Furthermore, after the experience with BART, it would certainly have been tested in great detail, before installation.

TLV trains can vary from a single vehicle to approximately 12 or 16, according to calculations on curvature. The Japanese plan trains of approximately 12 TLV vehicles together, each with their individual propulsion system and capable of operating separately, so that the control systems would be linked together.

Human engineers would be present to take over in case of emergencies, which necessarily have to be very rare, for the comfort and safety of the passengers. Speculatively, it appears more valuable in TLV system considerations to use womanpower in the form of stewardesses who are trained not only to optimize the comfort and convenience of the passengers, but also to handle the rare emergencies that can occur. At the speeds at which the TLVs would operate, the emergencies would need to be as rare as with aircraft, before such a system could be acceptable, and probably would need to be even more rare in terms of passenger-miles since the installation of TLV systems would be contingent on having sufficiently high demand in any case

There is a control system option which does not require that TLV trains stop at each station. It resembles the old Pullman car plan. Since TLV trains are made of separately propelled TLVs, individual TLVs can be designated for each station in iverse order. Thus, to disembark passengers at a station, the last TLV(s) in the train decouple, deaccelerate, and switch onto a siding at low speed. Similarly, embarking passengers enter a vehicle which switches from a siding and

accelerates to speed at the proper time to couple onto the front of a TLV train. The object detection radar or laser system can be used to control the coupling to the front of the TLV train. This option would permit higher average speeds and stations being located closer together.

Propulsion Systems for Tracked Levitated Vehicles

There are a wide variety of technical choices of propulsion systems for TLVs. From the standpoint of cost/benefit trade-offs, this is a blessing; however, from the viewpoint of decision-making in a democratic government, it is causing enormous confusion which can only be clarified by research and development.

In short, the major options are: (1) the use of a turbofan or turbo-prop with on-board fuel storage (no guideway electrification), but with questionable noise levels in the vicinity of the guideway, (2) on-board gas-turbine power-generation with any of the electromagnetic motors listed below, which probably also have unacceptable noise levels, since both gas turbine systems are well over 100 dB at 50 feet; and (3) preferably the vertically mounted two-sided linear induction motor (LIM), the most efficient design for a LIM with guideway power pickup. For the two types of MAGLEV vehicles, the magnetic suspension is consistent with superimposing a single-sided LIM, preferably with guideway power pickup. The high-speed power pickup problem can be avoided for repulsion MAGLEV by putting linear synchronous windings in the guideway. The linear synchronous guideway costs more but simplifies control problems since the vehicle is electromagnetically locked in.

The choice of propulsion system could be made on several grounds. For example, the cheapest propulsion system would be the on-board turbofan, but that would also be the least desirable and least comfortable for both the passengers and the neighbors of the TLV line. Since guideway construction costs are such a large fraction of the total cost, the political decision of installing TLV lines (which would cost several billions) will probably not be based upon small percentage reductions in cost but rather on designing the most acceptable system to everyone. Presumably, no shortcuts on safety, comfort, and convenience will be acceptable, and therefore, the quiet propulsion modes such as the linear induction motor or linear synchronous motor will be chosen even though the costs are slightly higher.

TLV Costs, Trip Times, Energy Requirements, Noise and Pollution

Costs. Certainly the most important fact in determining whether tracked levitated vehicle systems will be a major intercity mode in the future is their cost This high cost is about 80% guideway related. Such a high capital cost, measured in billions of dollars, necessarily means that a large demand, much greater than 10 million passengers per year, would be required in order to justify it. It also means that,

like the interstate highway system, a national decision would be required in order to build a TLV line in one or more of the high-density corridors.

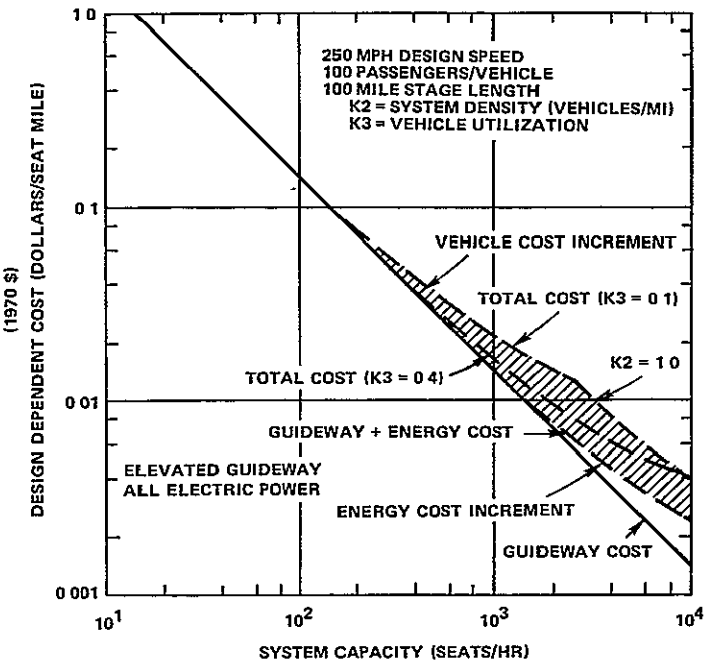
For the Japanese National Railway, the decision to plan a MAGLEV system was simplified by the long narrow shape of their country, problems in obtaining land for airports, and the already heavy use of the Tokkaido Line running through Japan. They already had the demand, their conventional railroads were running at capacity, and the annual increase was making it worse. For them, the commitment to a repulsion MAGLEV system for their new Super-Super Express was simple due to those economic factors, and the relatively quiet operation of repulsion MAGLEV. On-board noise was an important factor because about 40% of the TLV line would be in hard rock tunnels. Safe operation under power failure conditions was also a factor in their decision

There are enough trade-offs available among the different TLV concepts and enough uncertainties in the cost estimates that it is reasonable to discuss all three concepts under a single cost estimate. Where there are obvious differences in costs among the concepts, they will be cited but for most purposes the differences among the concepts is less than the uncertainty in the estimates.

Figures V-7 and V-8 show estimates made in 1970 dollars for TACV lines as a function of system capacity.[3] When translated into cost of system per kilometer and corrected by an average inflation figure to 1974 dollars, this TRW system cost estimate is $2.2 million per kilometer. This cost estimate is too low for several reasons. Cost of acquiring the right-of-way has not been included. More importantly, from the work of Professor Leonard Merewitz of the University of California, Berkeley, on cost overruns in public works projects, we can conclude that the costs in each category have been systematically underestimated.

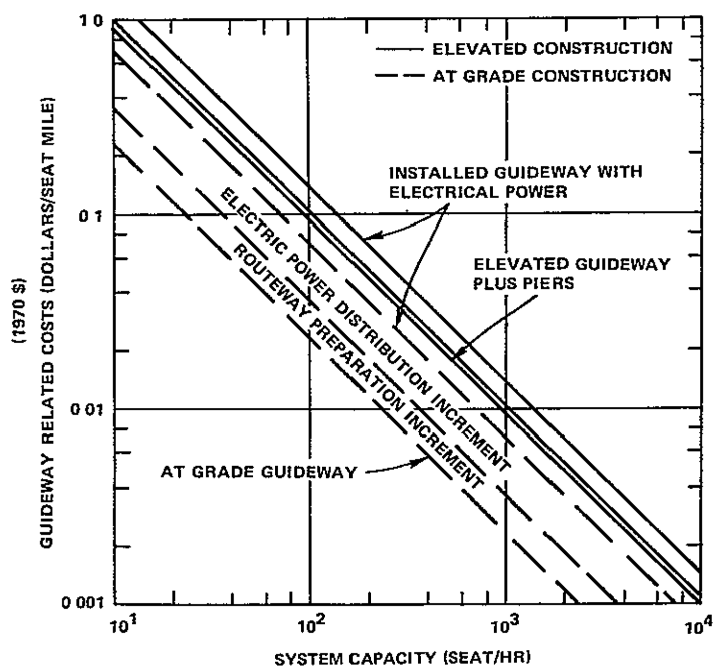
This is also evident when you consider that BART cost $12 5 million/km and the new Washington, D.C., METRO will exceed $30 million/km. Of course, the percentage of tunneling affects the cost enormously but a discrepancy is still apparent. We had hoped to use the disaggregate analysis performed by Professor Merewitz[7,8] to disaggregate and correct the TLV cost estimates by TRW, Philco-Ford, and MITRE. However, this simply was not possible for the author to accomplish in the time allowed; in fact, after trying, it looks as if it could easily be a one man-year effort. Therefore, the best available data will be presented and some summary adjustments made.

The basic problem with previous cost estimates is a systematic trend to choose the cheapest option for each situation, such as more at-grade guideways and less elevated and tunneled sections than desirable. Also, contingencies such as moving utilities and over or underpasses to avoid grade crossings are not included.



Source TRW

Figure V-7. TACV MAJOR SYSTEM COSTS



Source TRW

Figure V-8. TACV GUIDEWAY RELATED COSTS

Tables V-1 and V-2 give MITRE's cost estimating data.[2] Table V-3 gives their system cost information for four corridors. Table V-4 gives the breakdown for those four corridors. Tables V-5 and V-6 give Philco-Ford estimates for repulsion MAGLEV guideways.[5] They have made some innovations in prefabricated box beam construction techniques which reduce basic costs.

Table V-7 gives typical expected fares, patronage, and breakeven patronage, Figure V-9 indicates how the breakeven fare varies with patronage. Trip times at 480 km/hr are shown in Table V-8. They compare favorably with airline travel between the same city pairs.

The demand required for TLV lines to be economic is from 10 million to 40 million passengers per year, depending on the corridor. Demand projections for 1985 and 1995 made by Peat, Marwick, and Mitchell & Co. for several corridors are shown in Table V-9. It is apparent that the total demand is adequate for TLV lines in several corridors, especially the Northeast and California corridors, provided that an adequate percentage, ∿30%, of travelers chose the TLV mode

Table V-1

TLV INVESTMENT COST ESTIMATING RELATIONSHIPS

Element	Unit Costs (millions of 1972 dollars)	Notes
Storage and Service Yards	11/Facility	Based on NEC estimate
Major Overhaul Shop	2/Facility	Based on NEC estimate
Terminals		
Suburban	9/Facility	Based on NEC estimates
Downtown	13/Facility	
Underground	31/Facility	
Electrification	.576/Route-Mile	Includes substation costs
Control and Communications	.180/Route-Mile	No foreign obstacle detection; similar to "automatic train operation" costs based on New Tokaido Line & BART
Land		
Urban California	1.3/Route-Mile	
Urban Elsewhere	2.75/Route-Mile	Based on NEC estimate
Rural California	.08/Route-Mile	
Rural Elsewhere	.16/Route-Mile	Based on NEC estimate
Route Preparation (at grade guideway)	1.36/Route-Mile	Average NEC estimate
Major Bridges	18.6/Bridge-Mile	Based on NEC estimate
Tunnels	29.8/Tunnel-Mile	Based on NEC estimate
Guideway		
At-Grade	1.10/Route-Mile	MITRE Corp. estimates for U-shaped guideway
Elevated	2.5/Route-Mile	
Vehicles	1.56/Vehicle	Average based on fleet size of 100

Source: MITRE Corp.

Table V-2

ESTIMATING RELATIONSHIPS FOR ANNUAL OPERATING COST

Item	Units	TLV (TACV)
Power	\$/Car Mile \$/Train Mile	.179 --
Crew	\$/Train Mile	.20
Vehicle Maintenance[a]	\$/Car Mile	.764
Guideway Maintenance	$\$10^3$/Route Mile	10.0
Power Maintenance[a]	$\$10^3$/Route Mile	19.5
Control Maintenance[a]	$\$10^3$/Route Mile	7.24
Indirect Operating Costs per Mile[b]	\$/Passenger	.015
Terminal Operations and Maintenance[c]		
Urban	$\$10^3$/Facility/Yr.	100 + .5 * (PPH)
Suburban	$\$10^3$/Facility/Yr.	50 + .4 * (PPH)

a. Vehicle, Power, and Control Maintenance Costs include 66% burden.

b. Indirect operating costs are those incurred in providing services, they are not directly related to vehicle operation. Some of the costs for passenger services on board accrue on an hourly basis (e.g., cabin attendants); therefore, the "per mile" costs would be less for higher speed service.

c. Fixed Operating Cost plus Variable Cost per Peak-Hour Passenger (PPH) Demand.

Source: MITRE Corp.

Table V-3

TLV SYSTEM COSTS
(1972 Dollars)

Corridor	Total Investment (millions) ROW	Total Investment (millions) Vehicle	Annualized Investment Cost (millions) ROW	Annualized Investment Cost (millions) Vehicle	Annual Operating Costs: Fixed (millions)	Annual Operating Costs: Variable per Car Mile	Annual Operating Costs: Variable per Train Mile	Annual Operating Costs: Variable per Passenger Mile
Boston-Washington	$3,004	$5.30	$442	$0.72	$18.0	$0.94	$0.20	$0.015
Portland-Seattle	929	5.30	138	.72	7.8	.94	.20	.015
San Diego-Los Angeles	668	5.30	99	.72	5.9	.94	.20	.015
San Diego-Sacramento	3,394	5.30	504	.72	25.9	.94	.20	.015

Source. MITRE Corp.

Table V-4

TLV INVESTMENT COSTS
(Millions of 1972 Dollars)

Element	Corridor: Boston-Washington	Portland-Seattle	San Diego Los Angeles	San Diego-Sacramento
Yards & Shops	$ 46	$ 24	$ 24	$ 46
Terminals	211	53	44	97
Electrification	256	96	65	367
Control & Communication	80	30	21	115
Route Preparation & Guideway Construction[a]	1,854	664	457 (370)	2,559 (2,080)
Land	557	62	57	210
Subtotal	$3,004	$929	$668 (581)	$3,394 (2,915)
Vehicles[b]	211	(8)	15	42
Total Cost	$3,215	$937	$683 (596)	$3,436 (2,957)

a. The lower values, in parenthesis, are in accordance with lower cost estimates established by the RAND Corporation in an unpublished study for the Department of Transportation, Office of Assistant Secretary for Research and Technology. The lower Route Preparation and Guideway Construction costs reflect the RAND assumptions of (1) no tunnels, and (2) approximately 50% of total mileage elevated and 50% at grade.

b. Vehicle requirements for initial year of operation; those for Portland-Seattle wre based on a minimal level of service, otherwise, based on demand. The demand estimates used for NEC and the Portland-Seattle corridor are based on a fare of $3.44 + .097/mile and for the California corridor a fare of $2.51 + .057/mile. Investment cost for TACV vehicles is estimated as $1.56 million per vehicle.

Source: MITRE Corp.

Table V-5

ESTIMATED ELEVATED GUIDEWAY COST
(Double Track)

	Total Cost (thousands of dollars per km)
Levitation-Guidance Components	
Aluminum	$506.3
Shop Fab	101.4
Attach Hardware	126.6
Field Installation	227.7
Subtotal	$962.0
Girder and Substructure Construction (Twin "T")	
Girders (22.8 m span length)	$2,050
Pier (6.85 m column height)	212
Footing (spread footing--pile footing)	217-505
Subtotal	$2,479-$2,767
Total, Guideway Fabrication	$3,441-$3,729
Land	$111-234

	Alternative Design No. 1	Alternative Design No. 2
Right-of-Way Width	15 m	31.5 m
Right-of-Way Area	3,6 acre.km	7.8 acre/km
Cost Assumption	$30K/acre	$30K/acre
Total Cost (thousands of dollars per km)	$3,552-$3,840	$3,675-$3,963

Source: Philco-Ford.

Table V-6

COSTS OF BASIC GUIDEWAY
(750 km Corridor)

Component	Percent of Total Length	Length (km)	Unit Cost, $\$10^3$	Total Cost, $\$10^6$
Bridges	1	8	$ 7,840	$ 62.72
Tunnels	4	30	23,000	690.00
Elevated (Spread Footing)	8	60	3,676	220.56
Elevated (Pile Footing)	8	60	3,964	237.84
At Grade	79	592	2,024	1,198.21
Total				$2,409.33

Source: Philco-Ford.

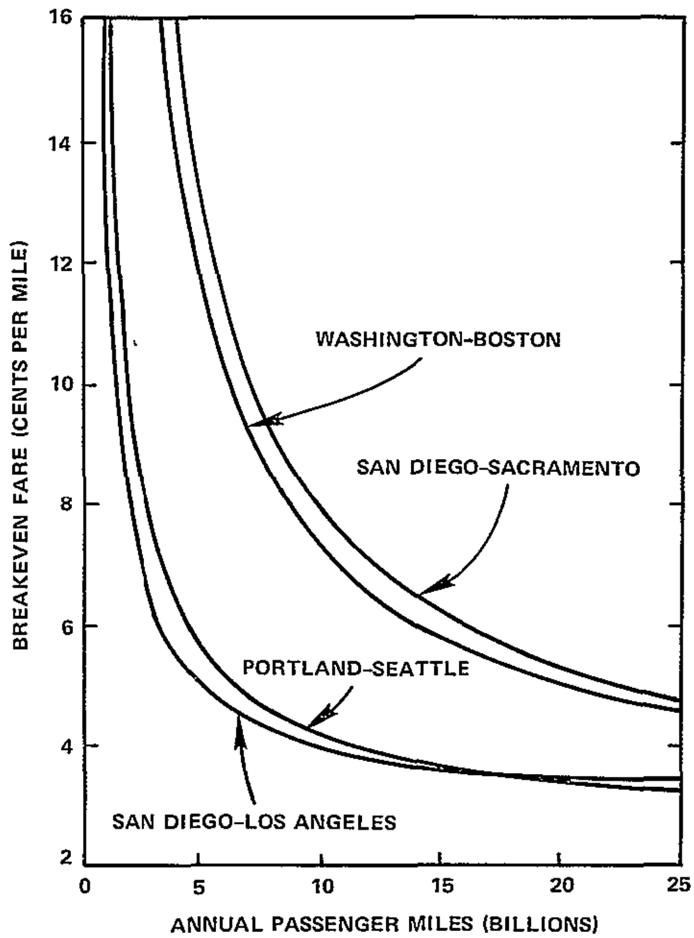
Table V-7

TLV BREAKEVEN PATRONAGE

System/Corridor	Average Trip Distance (miles)	Fare Structure	Average Fare (cents/pax mi.)	Expected 1985 Patronage (mil pax)	Breakeven Patronage	
					Annual Passengers (millions)	As % Total Demand All Modes in 1985
Boston-Washington	135	A	12.25	40	35	12
Portland-Seattle	166	A	11.77	1.5	9.6	210
San Diego-Los Angeles	114	A	12.71	9.3	9.4	19
San Diego-Los Angeles	114	B	10.11	12.5	13	26
San Diego-Sacramento	180	A	11.61	20.5	33	34
San Diego-Sacramento	180	B	9.36	27.6	42	43

Note: Fare Structure: A = \$3.44 + \$.097/mile
B = \$1.72 + \$.086/mile

Source: MITRE Corp.



Source MITRE Corp

Figure V-9. BREAKEVEN FARE VARIATION WITH PATRONAGE

Table V-8

TRIP TIME COMPARISON BETWEEN CENTRAL BUSINESS DISTRICTS

	TLV Line Haul Time (hrs)	Airline[a] Flight Schedule (hrs)	CBD to CBD (hrs)
New York-Boston	0.9	0.9	2.2
New York-Washington	1.0	0.9	2.2
New York-Philadelphia	0.4	0.5	1.9
New York-Albany	0.6	0.6	2.0
New York-Buffalo	1.0	1.0	2.3
Boston-Washington	1.8	1.1	2.1
Boston-Philadelphia	1.3	1.0	2.0
Pittsburgh-Detroit	1.0	0.8	2.2
Chicago-Detroit	1.0	0.8	2.4
Chicago-Milwaukee	0.4	0.5	1.8
Los Angeles-San Diego	0.5	0.5	1.4
Los Angeles-Las Vegas	1.0	0.8	1.8
Los Angeles-San Francisco	1.5	1 0	2.4

a. *Official Airline Guide*, block to block and ground transportation.

Source: MITRE Corp.

Table V-9

TOTAL TRANSPORTATION DEMAND PROJECTIONS
(Millions of Annual Passenger Trips by All Modes)

Corridor	Year 1975	Year 1985	Year 1995	Percent Growth 1975-1985	Percent Growth 1985-1995
Chicago-Detroit	6.2	8.0	10.2	29%	27%
Portland-Seattle	3.1	4.4	5.8	42	32
San Diego-Los Angeles	33.7	49.7	68.0	47	37
San Diego-Sacramento	65.3	94.8	128.3	45	35
Washington-Boston	203.0	300.0	444.0	48	48

Source: Prior studies by Peat, Marwick, Mitchell & Co.

Investment Cost Summary. Merewitz has found that eight rapid transit projects cost an average of 1.5 times the original estimate, including infaltion. About half of the increase was due to design changes, e.g., more elevated or tunneled guideways. Including Professor Merewitz's factor, as estimates for this intercity transportation technology assessment, we suggest $5.0 million/km ($8.06 million/mile) for a nonelectrified guideway with a minimum of tunnels; and $7.5 million/km ($12.1 million/mile) for an electrified guideway, possibly a linear synchronous motor, and a larger fraction of tunnels and elevated line. These corrected estimates are intended to include everything: vehicles, right-of-way, maintenance facilities, design changes, and allowance for inflation to 1974 dollars.

Vehicle cost included in the above is about $1,841,000 per car (including spares) based on pages 5 to 19 of the *High Speed Ground Transporation Alternatives Study*, DOT, January, 1973, increased by 18% for inflation from 1972 to 1974.

Operating Costs Summary. The best available data appear to be those in Tables V-2 and V-3. The data in Table V-3 are based on 1972 dollars and estimated for specific route studies, an aspect affecting the fixed annual cost due to terminal operating and maintenance costs. For the two most likely routes, Washington-Boston and San Diego-Los Angeles, the fixed costs are

$$\frac{\$18,000,000}{444 \text{ route miles}} = \$40,540/\text{route miles and}$$

$$\frac{\$5,900,000}{114 \text{ route miles}} = \$51,750/\text{route mile},$$

respectively. The average is about \$46,000/route mile The other operating cost terms are dependent on car-miles, train-miles, and passenger-miles.

From the data in Table V-3 then, the cost per train-mile is·

$$\text{Cost per train-mile (\$)} = 0.20 + 0.94C + 0.015\ CNlf + \frac{46,000}{T}$$

$$= 0.20 + 0.94C + 0.015\ CNlf + \frac{46,000\ CNlf}{D}$$

where

C = number of cars per train
N = number of seats per car
lf = load factor
T = train trips per year

$$= \frac{D}{CNlf}$$

D = annual one-way passenger trips

The cost per passenger mile is

$$\text{Cost/pass-mile} \quad (\$) = \frac{0\ 20}{CNlf} + \frac{0.94}{Nlf} + 0.015 + \frac{46,000}{D}$$

Now assuming 75 passengers per car and 4 cars per train, the cost equation becomes

$$\text{Cost per train mile (\$)} = 0.20 + 0\ 94(4) + 0.015(4)(75)lf + \frac{46,000}{\left(\frac{D}{(4)(75)lf}\right)}$$

$$= 3.96 + lf\left[4\ 5 + \frac{13.8 \times 10^6}{D}\right]$$

and

$$\text{Cost/pass-mile (\$)} = \frac{0.20}{300lf} + \frac{0.94}{75lf} + 0.015 + \frac{46{,}000}{D}$$

$$= 0.015 + \frac{1}{lf}\,[0\ 0132] + \frac{46{,}000}{D}$$

To adjust these equations to 1974 dollars, a factor of 1.18, the increase in the Consumer Price Index from 1972 to 1974, is applied.

Then in 1974 dollars,

$$\text{Cost per train mile (\$)} = 0.236 + 1.11C + 0\ 018CNlf + \frac{54{,}300\ CNlf}{D}$$

$$\text{Cost per pass-mile (\$)} = \frac{0.236}{CNlf} + \frac{1.11}{Nlf} + 0.018 + \frac{54{,}300}{D}$$

And with 4 cars and 75 passengers per car,

$$\text{Cost per train mile (\$)} = 4.67 + lf\left[5.31 + \frac{16.3 \times 10^6}{D}\right]$$

$$\text{Cost per pass-mile (\$)} = 0.018 + \frac{1}{lf}\,[0\ 0156] + \frac{54{,}300}{D}$$

Trip Time. The overall trip time (block time) of a ground vehicle is the time at full cruise speed plus the time to accelerate and decelerate plus the time spent in stations (dwell time). Assuming a 3-minute station dwell time and an acceleration and deceleration rate of 0.15 g, a series of block time curves for various speeds and numbers of intermediate stops are plotted versus distance in Figure V-10. For a 375-statute-mile trip with 2 stops and a 375 mph cruise speed, the block time is 1.19 hours. The corresponding effective block speed is 315 mph.

Energy Consumption. The energy usage of TLVs compared to other transportation modes is shown in Figure V-11

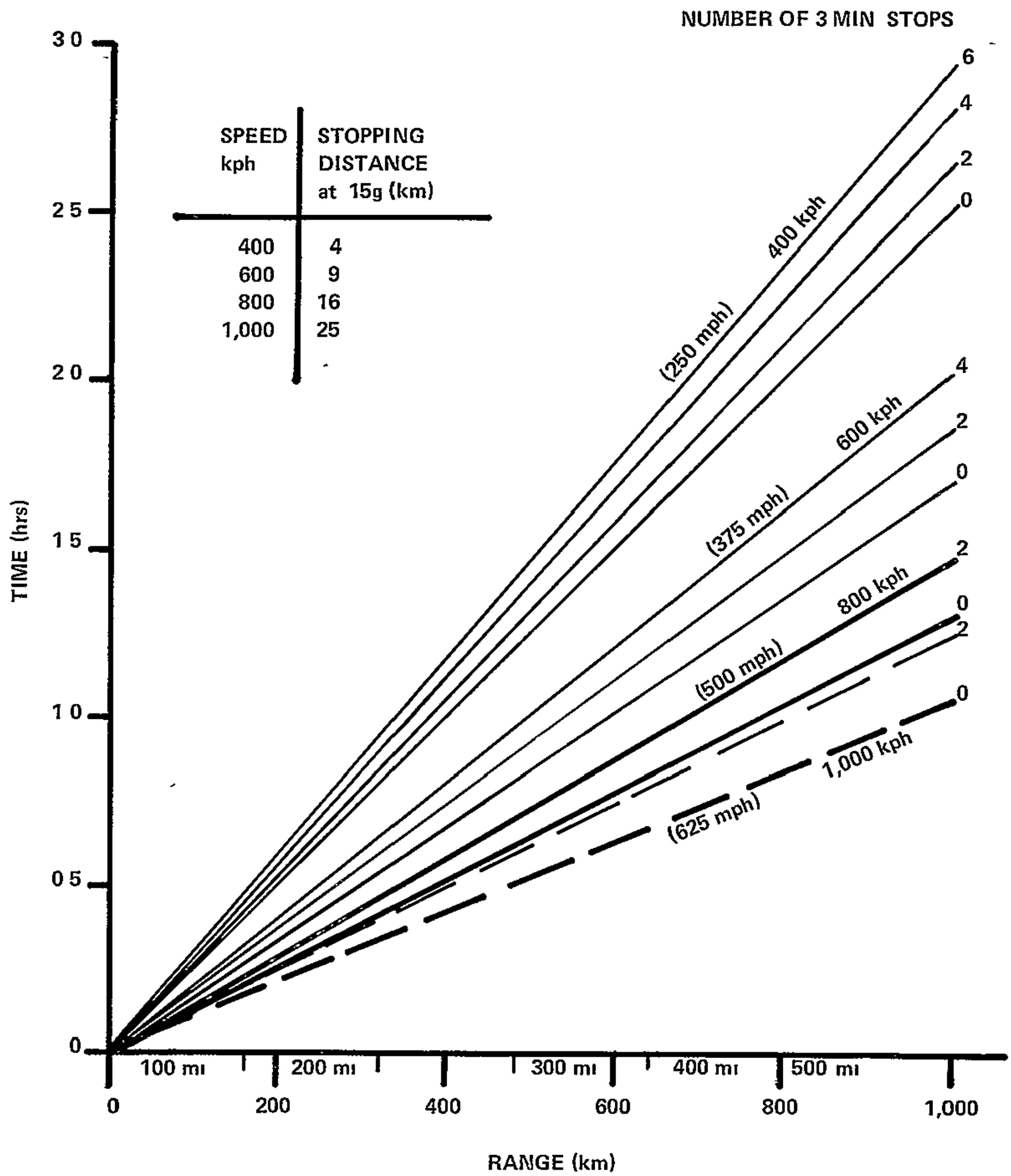
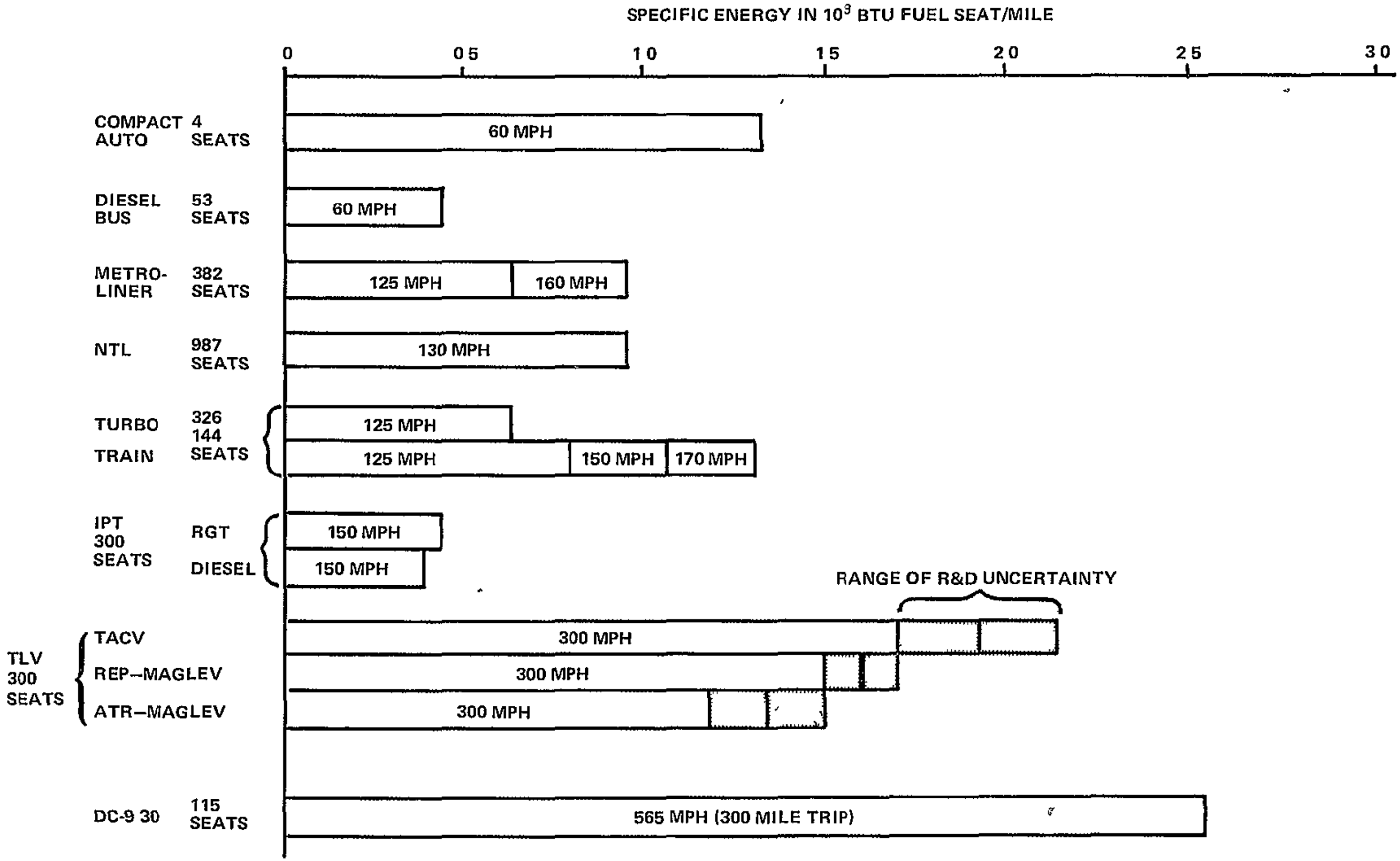


Figure V-10. BLOCK TIME VS RANGE FOR TLVS IN A 1,000 km CORRIDOR FOR VARIOUS SPEEDS AND NUMBER OF STOPS



Source MITRE CORP

Figure V-11. COMPARATIVE ENERGY CONSUMPTION

<u>Noise</u>. Since true TLVs do not exist commercially, most data must be estimated. Approximate noise levels for TLVs are compared with many other vehicles in Figure V-12 while noise trends for tracked vehicles only are shown in Figure V-13. Noise levels for TACVs should be very high due to the air cushions and aerodynamics even if the propulsion is noiseless. Most estimates point to at least the 90-100 dBA range at 50 feet, given current technology for speeds greater than 200 mph as shown in the following tabulation.

NOISE LEVEL ESTIMATES FOR
TACVs AT 50 FEET FROM THE VEHICLE

Characteristics	Speed (mph)	dBA
With well-muffled propulsion	200	93-100
Engines and compressors	300	98-105
Air cushion jet only	200	90
	300	95

Note. There is a marked increase in the noise level as the speed of the TACV increases.

Source: Wilson, Ihrig, and Associates, Inc., *Noise and Vibration Characteristics of High Speed Transit Vehicles*, U.S. DOT Report No. OST-ONA-71-7, June 1971.

<u>Pollution</u>. Total emissions of the major pollutants, including those from electric generating plants are compared for TLVs and other vehicles in Figure V-14.

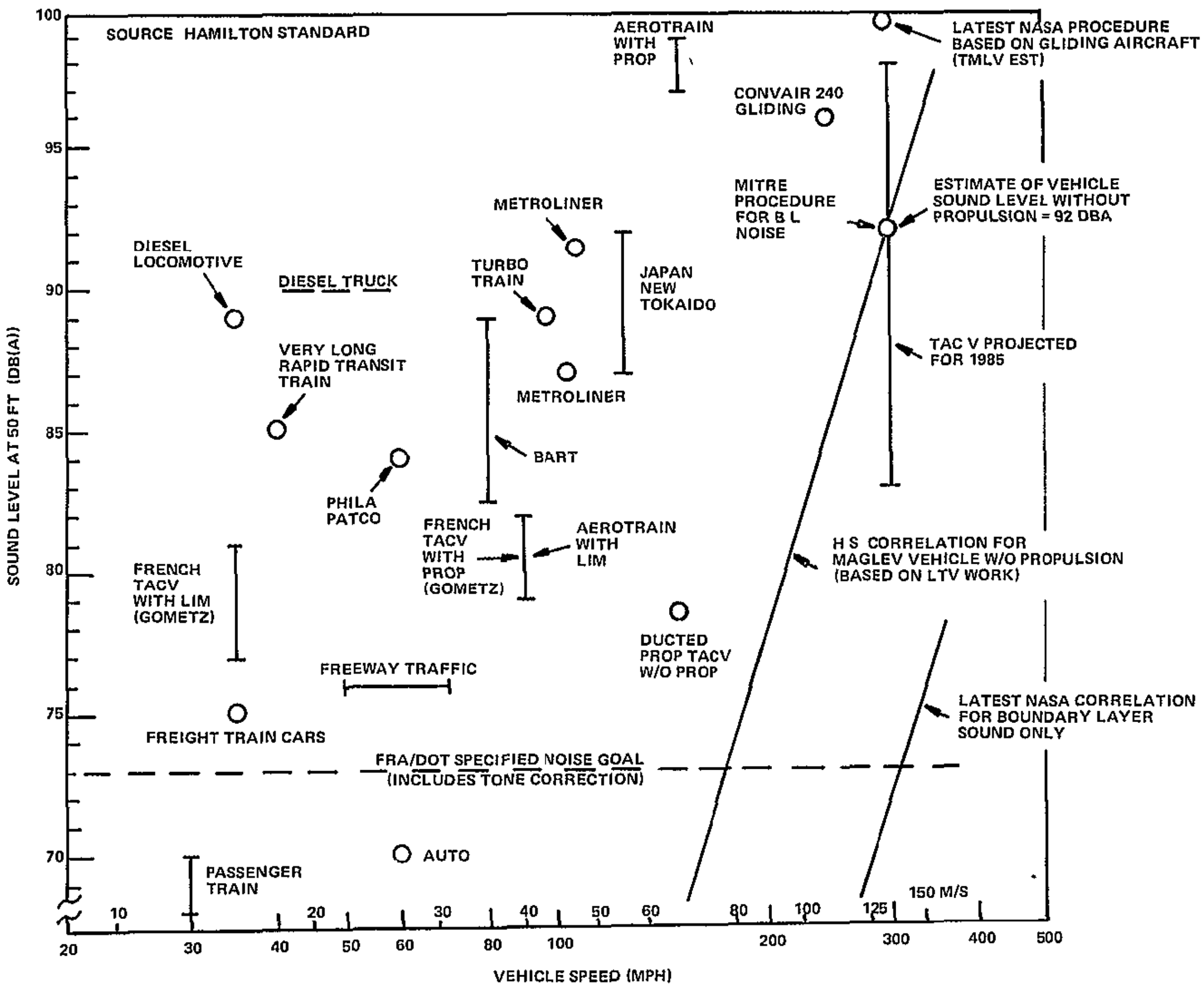


Figure V-12. NOISE DATA SUMMARY AND NOISE CORRELATION FOR UNPOWERED MAGLEV VEHICLE

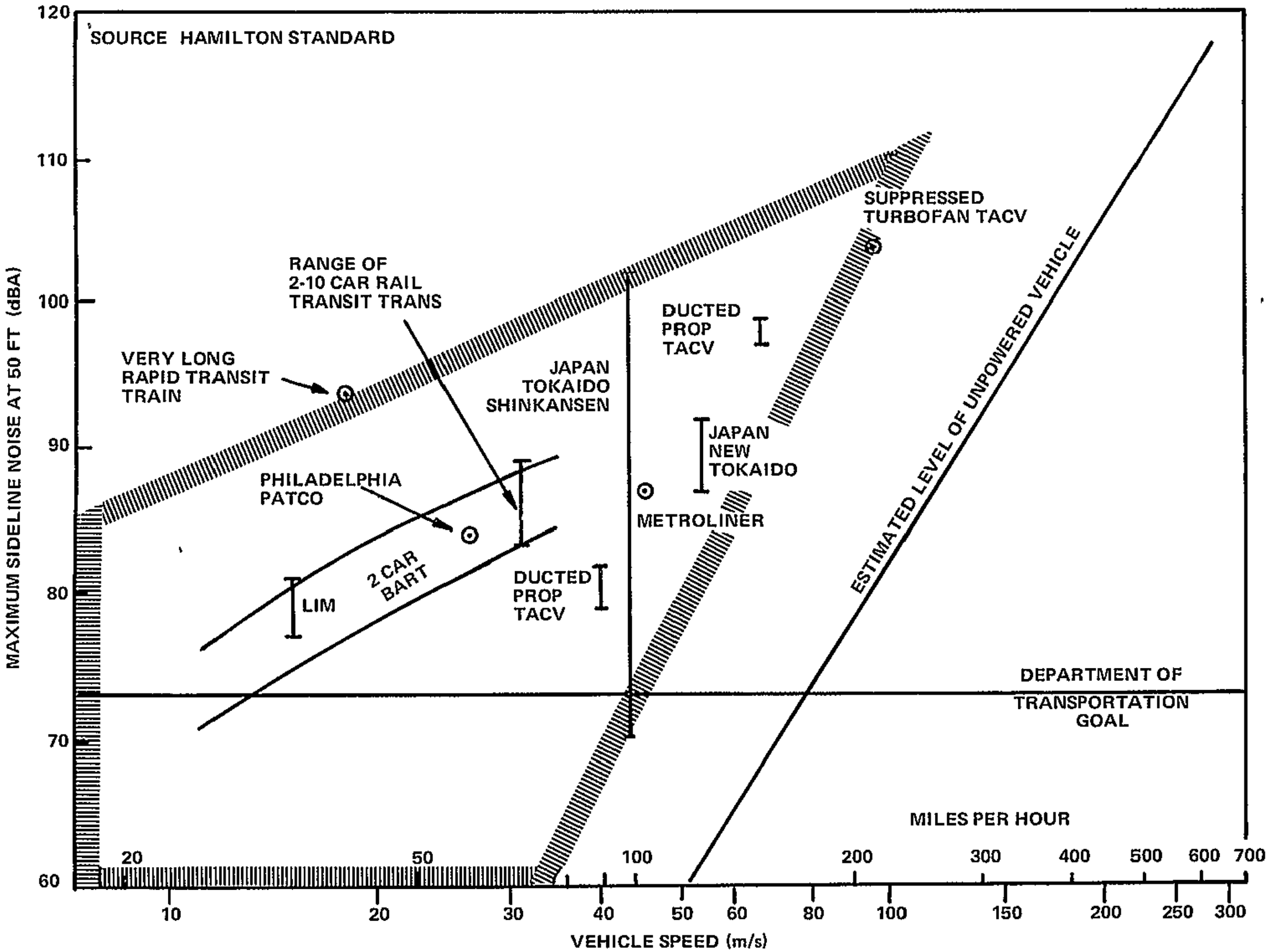
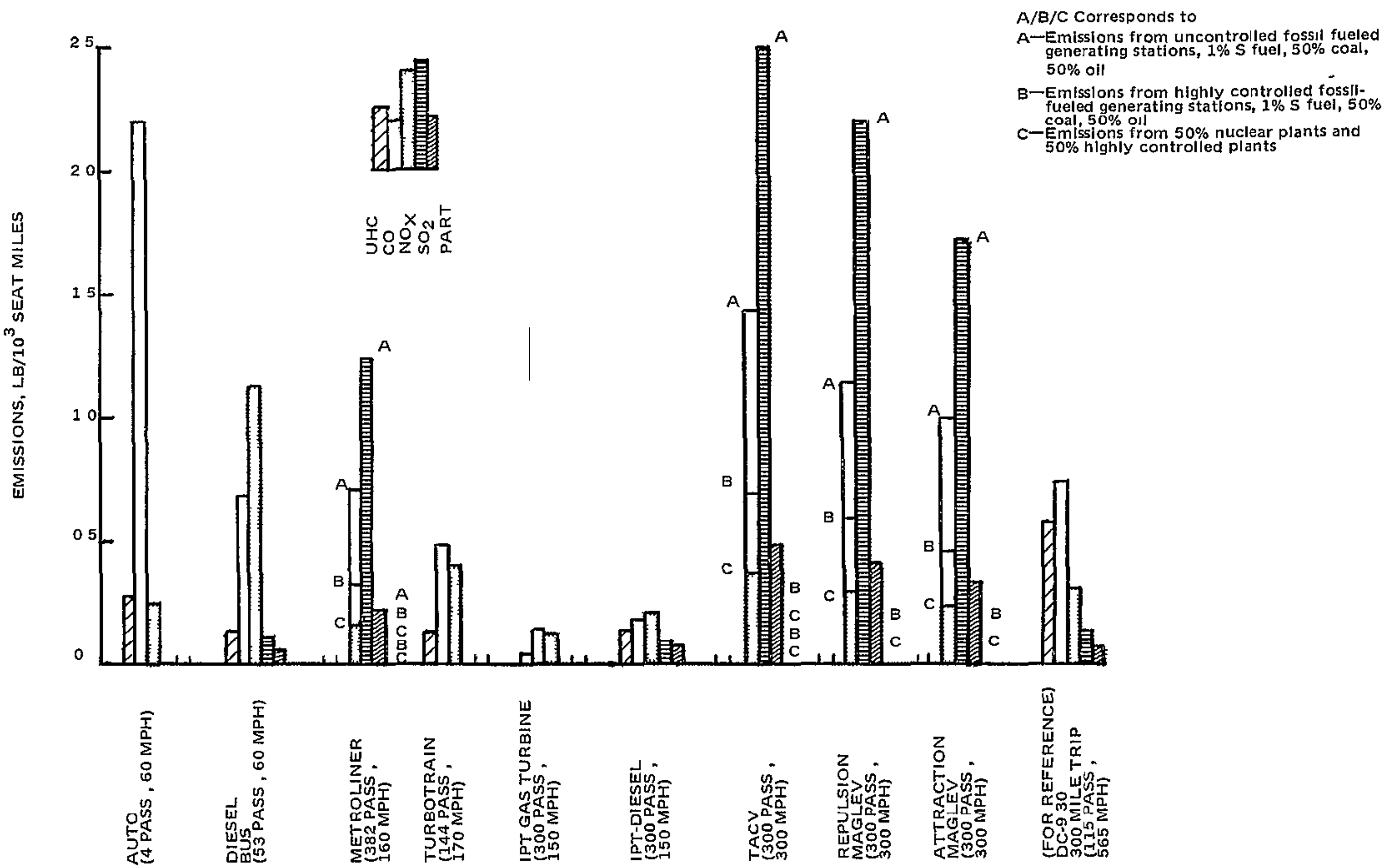


Figure V-13. VEHICLE NOISE TRENDS



Source MITRE CORP

Figure V-14. POLLUTANT EMISSION COMPARISON

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VI. HIGHWAY TRANSPORTATION SYSTEMS

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VI. HIGHWAY TRANSPORTATION SYSTEMS

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VI. HIGHWAY TRANSPORTATION SYSTEMS

Highways

Frank Chilton, Ph.D.
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Expected Trends and Innovation in Highways

Intercity highway construction technology is not expected to change much for at-grade highways, the largest percentage built. The careful grading, road bed, and subgrade composition techniques developed during the construction of the Interstate Highway System may seem to take a long time, but are essential to prevent gradual settling and "washboarding" of the highway.

The use of prefabricated and prestressed concrete overpass and elevated members shows some promise, but due to their massiveness and the difficulty in transporting them, this technique appears to be useful only in certain locales.

The big innovation in intercity highways appears to be coming in the urban portion where it is becoming cost effective to use cut-and-cover tunneling technology improvements in order to have the urban portions of the freeway underground The first such section is now operational in Washington, D C

Other important innovations for new and existing highways are expected in safety modifications. The technology now exists for impact absorbing barriers, highway dividers and barriers which return a car going off the road into its lane; and breakway sign, lighting, and utility poles. All of these improvements, when implemented, should substantially reduce the severity of the 40% single vehicle accidents, and to a lesser extent reduce multicar collisions and their fatality rate.

Highway Costs

The practice in highway cost estimation is to use average figures since every highway project differs due to local geology changes. The California Division of Highways has supplied such average cost data for the six years preceding 1970. Since that time, Federal Highway Administration (FHWA) construction cost indicators show a 104% increase in the average cost of highway construction. Combining these figures gives a rounded average cost of highway construction in 1974 dollars as presented below Right-of-way costs are not included

Number of Lanes	Urban Projects (million $/mile)	Rural Projects (million $/mile)
4	$3.3	$1.5
6	4.6	2.1
8	5.9	--

Source: California Division of Highways, *1970 Annual Report* and *Department of Transportation News*, FHWA, May 9, 1975.

Automobiles

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Expected Trends and Innovations in Automobile

The automobile has been with us for 80 years and we do not expect that generality to change during the next 50 years. There will always be a significant fraction of intercity transportation in private vehicles. What mode offers such privacy and convenience, especially for nonbusiness travel? The fraction may not be as large as the 85% for short and medium trips, and 50% for trips beyond 1,000 miles which has been estimated as the modal split now. Also, autos may look somewhat different outside and we certainly expect them to look different inside with better use of interior space. Major innovations are expected to improve safety, emission control, and energy usage, especially the latter, since the automobile now uses about 30% of the petroleum consumed in the United States.

Future improvements in automobiles can be classified as alternative engines or as vehicle improvements such as transmissions, accessories, tires, or body design and construction. Although alternative engines offer considerable potential for energy and pollution reductions, there are difficult technical problems to be solved and huge investments to be made. Therefore, the vehicle improvements can be expected to appear in service earlier than new types of engines. These vehicle improvements are discussed first followed by consideration of alternative engines.

Vehicle Improvement

The need for improvements to automobiles in both pollution and energy characteristics is well known. The ugly skies of many cities document the pollution problem. Hopefully the pollution problem is well on the road to control. Table VI-1 from Reference 13 summarizes the progress since 1968. The California 1975 levels represent reductions of about 90% in hydrocarbon exhaust emissions (HC), 90% in carbon monoxide (CO), and 60% in nitrogen oxides (NO_x) from the highest previous levels. The federal 1977 emission levels will show reductions of about 95% in HC and CO and 60% in NO_x.

Table VI-1

EMISSION STANDARDS FOR LIGHT DUTY VEHICLES

Applicable Date	HC	CO (grams/mile)	NO_x
Uncontrolled	(8.7)	(87)	(3.5)
1968	a	a	(4.3)
1970	4.1	34	(5.0)
1972	3.0	28	(5.0)
1973	3.0	28	3.1
1974	3.0	28	3.1 [2.0][b]
1975 Federal Auto	1.5	15	3.1
1975 Federal LD Truck	2.0	20	3.1
1975 California	0.9	9	2.0
1977 Federal Auto	0.41	3.4	2.0
1978 Federal Auto	0.41	3.4	0.4

Note: All emission standards listed are expressed in terms of the 1975 Federal Test Procedure (FTP). Figures in parentheses show actual values during periods when no federal emission standard was in effect.

a. Standards for 1968 and 1969 were expressed in concentration by volume: 275 ppm for HC, and 1.5% CO.

b. 2.0 NO_x on 1974 California cars.

The magnitude of the energy problem is shown in Figures VI-1 and VI-2 from Reference 13. Figure VI-1 shows the average fuel economy, in miles per gallon, of the U S. passenger car fleet from 1950 to 1972. About a 10% decline occurred over the period due to increasing weight and accessories and in the later years due to pollution control devices and techniques.

Figure VI-2 (Reference 13) shows an estimate of the U.S. energy percentage used by motor vehicles. Since about 45% of our energy comes from petroleum, the motor vehicle share, including trucks and buses, of petroleum consumption is over twice its share of total energy or about 43%.

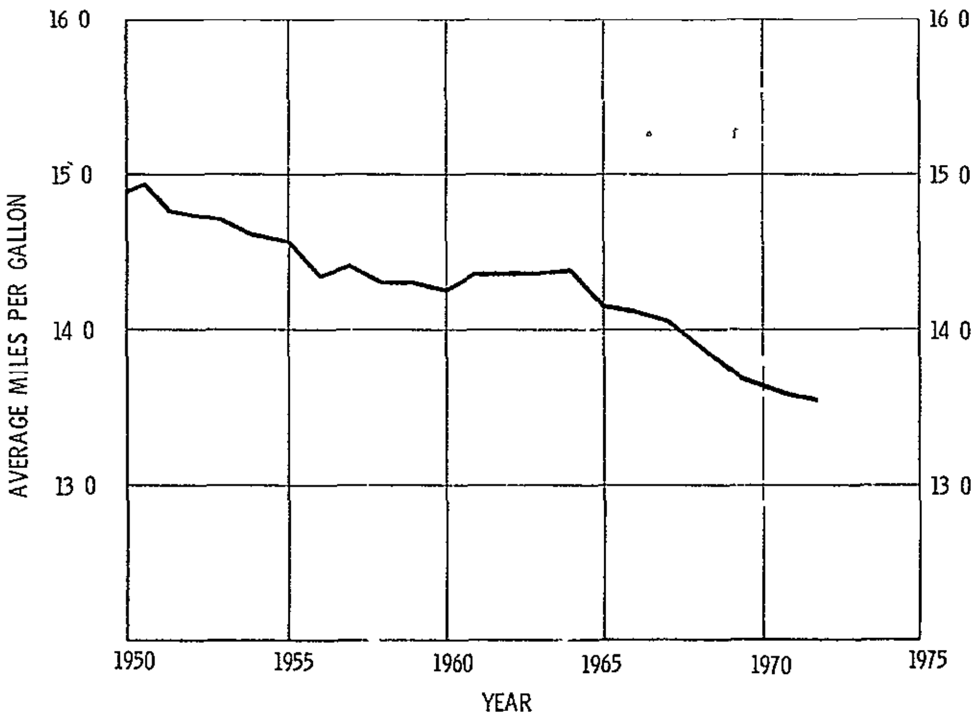
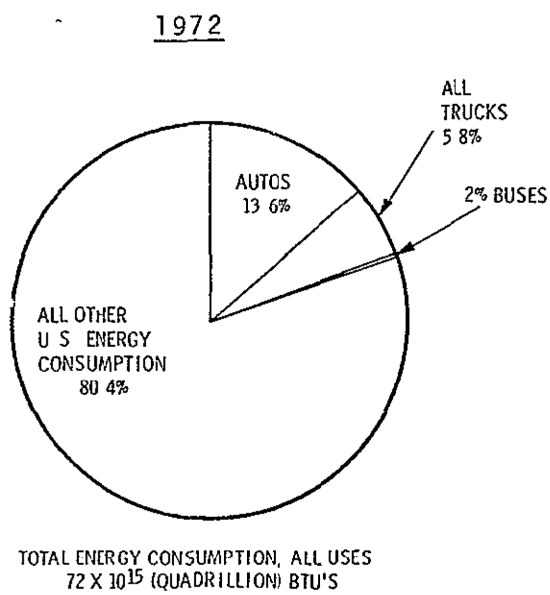


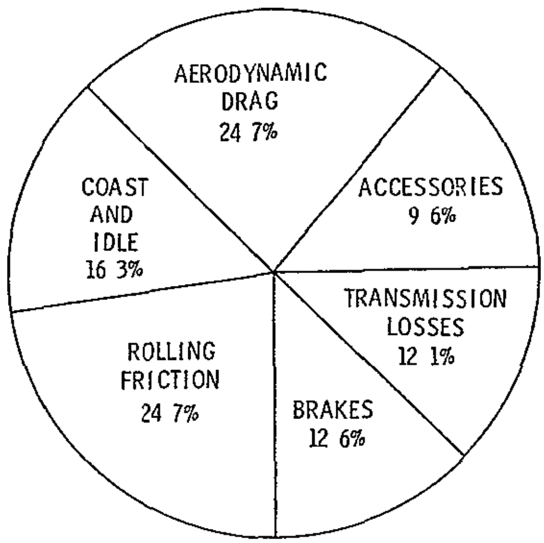
Figure VI-1. AVERAGE FUEL ECONOMY (mpg) OF U.S. PASSENGER CAR FLEET, 1953-1972



Sources (1) U S Bureau of Mines Minerals Yearbook
(2) FHWA Highway Statistics 1972

Figure VI-2. SHARE OF U.S. ENERGY CONSUMED BY MOTOR VEHICLES IN 1972

Figure VI-3 shows the breakdown of energy usage in a typical automobile. Based on Reference 13, the chart shows about 25% of the energy being used to overcome aerodynamic drag, 25% consumed by rolling friction, 12% being used by transmission losses, 12% by brakes, 10% by accessories, and the remainder, 16%, being used in coast and idle. These data are based on the EPA Composite City/Highway Test Cycle where 55% is assumed to be city usage and 45% highway driving.



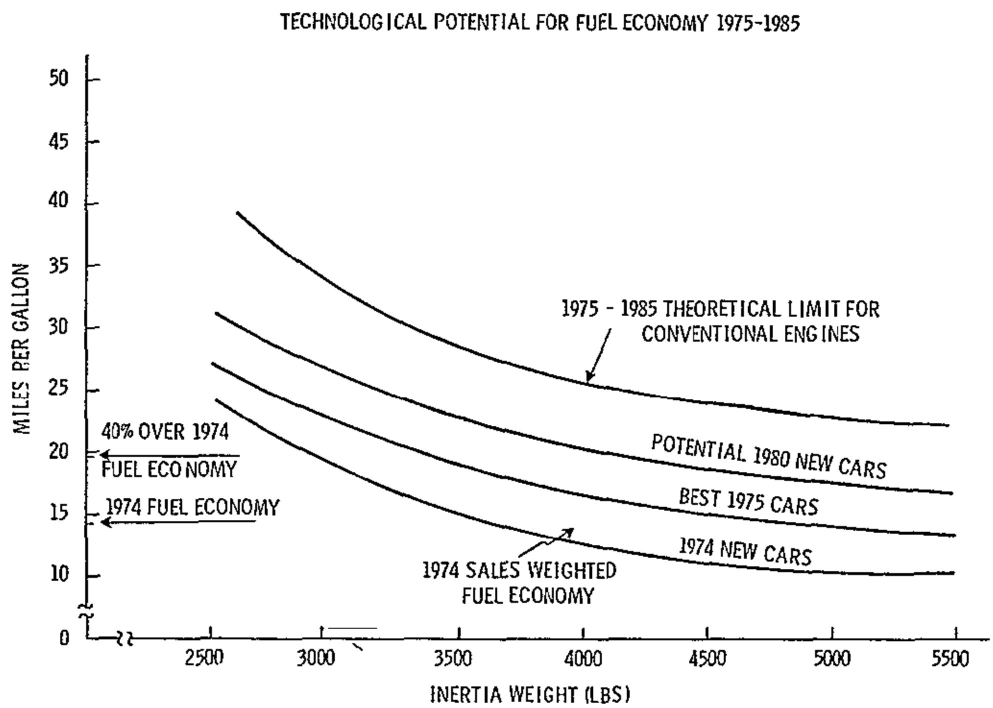
SOURCE DOT/TSC, ANALYSIS OF 1973 AUTOMOBILES AND INTEGRATION OF AUTOMOBILE COMPONENTS RELEVANT TO FUEL CONSUMPTION (SEPT 1974) (DRAFT)

Figure VI-3. APPORTIONED ENERGY REQUIREMENTS FOR REFERENCE 3,500-POUND OPERATION IN THE EPA COMPOSITE CITY/HIGHWAY TEST CYCLE

Figure VI-3 indicates the aspects of automobile design that may yield energy efficiency improvements. The aerodynamic drag is dependent upon the drag coefficient, a measure of the drag qualities of the shape, and the frontal area. Rolling friction is a function of tire qualities and weight. The energy lost in the brakes is dependent upon the weight, while the transmission losses are caused by fluid and gear friction losses. Losses in accessories, such as water and fuel pumps, generators, air conditioners, and power accessory drives, could be reduced by raising the efficiency of those units and limiting their speeds to the minimum required for satisfactory operation.

The entire level of fuel usage required to overcome the various losses is a function of engine specific fuel consumption. The possibilities of alternative engines will be discussed in detail below. In terms of the vehicle itself, weight is the most fundamental parameter.

Figure VI-4 shows the statistical variation of the EPA composite cycle fuel efficiency with weight. Although the relationships are somewhat scattered, there is also a general correlation between engine displacement and vehicle weight. Weight can be reduced by redesigning a vehicle to use its internal space more efficiently, by a general chassis redesign, by substitution of lighter materials, and by reducing car size.



Source. Reference 13.

Figure VI-4. 1975-1985 TECHNOLOGICAL POTENTIAL FOR FUEL ECONOMY

Among the substitute materials are aluminum, plastic, and high-strength, low-alloy steel. Material availability and cost may limit aluminum use. Chassis redesign offers a promising potential in weight saving by using unibody construction, front-wheel drive, and independent rear suspension. The trend toward smaller cars will be largely driven by the price and availability of fuel and by the ability of manufacturers to maximize the use of internal space.

Aerodynamic drag will benefit from smaller car sizes and more attention to streamlining. Functional design to house power plant, occupants, and trunk space within the lightest, smallest envelope will be somewhat at odds with the desire for minimum drag coefficient. As a result, a reduction of 15% to 20% in drag is a reasonable target in the years ahead.

Radial tires have a beneficial effect on rolling friction. Gains of 2.5% to 4% have been estimated.

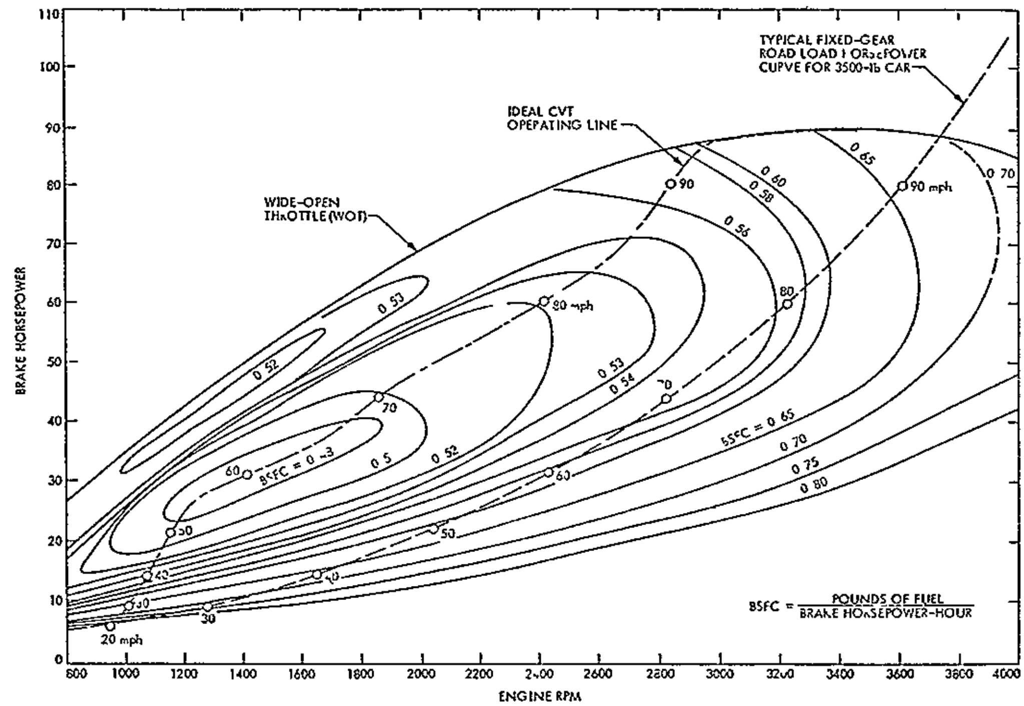
Improved accessories and speed-limiting accessory drives have a significant potential for reducing energy consumption. One suggestion has been a thermostatically controlled cyclic air conditioner which reduces the duty cycle of air conditioners to about one-third. Since the average fuel economy penalty of an operating air conditioner is about 6%, about 70% of automobiles have air conditioners, and assuming six months per year usage, the average fuel economy gain should be about 1.4%.

Transmissions serve as a link to match wheel and engine speed and torque requirements. The requirement for high torque for acceleration demands high engine power and engine speed (rpm). The gear ratio that provides this leads to excessive engine rpm for steady cruising when the power requirement is much reduced. Figure VI-5 shows the performance map for a spark-ignition (Otto cycle) engine. The contours of constant brake specific fuel consumption (BSFC) show that minimum BSFC is obtained for any given power output at a low value of rpm, i.e., a high torque and a high average cylinder pressure, b.m.e.p.. This also implies that a reduction in engine size, which leads to a higher b.m.e.p. in normal operation, is favorable to BSFC. Therefore, one means of improving fuel consumption is to reduce engine sizes at the expense of acceleration.

Figure VI-5 illustrates that the normal operating line in high gear lies far from optimum BSFC. A better match to optimize BSFC can be obtained by additional gear ratios, i.e., with a 5-speed manual or a 4-speed automatic transmission. The ideal would be a continuously variable transmission (CVT) with the gear ratio selected by both automobile speed and desired acceleration.

A "lock-up" device to eliminate the losses due to torque converter slip would further improve the efficiency of automatic transmissions. Such devices could prove this "lock-up" capability in high gear only or in all but the lowest gear.

The CVT requires considerable development and is probably at least ten years away. The other concepts, additional gear ratios and "lock-up," could be much more easily implemented.



Source: Reference 10.

Figure VI-5. TYPICAL FUEL CONSUMPTION MAP FOR OTTO CYCLE ENGINE

The potential gains from these nonengine sources are summarized in Table VI-2 and Table VI-3. Table VI-2 and the "intermediate" improvements of Table VI-3 are based on a 1980 time period, while the "longer term" of Table VI-3 refers to 1985 and beyond. Although there is considerable disagreement in individual items, overall gains of 20% to 30% are foreseen in both cases by 1980 due to vehicle improvements. Table VI-3 indicates a potential gain in the 1980s (longer term) up to about 40%.

Alternate Power Plants

Six alternative automotive power plant systems are considered in this report.

- Stratified-charge internal combustion engines
- Diesel
- Gas turbine (Brayton cycle) engine
- Steam (Rankine cycle) engine
- Stirling engine
- Electric vehicles

Table VI-2

FUEL ECONOMY IMPROVEMENTS THROUGH TECHNOLOGY CHANGE
BY 1980 COMPARED TO 1974

Technological Change	Fuel Economy Improvement in Percent of mpg		
	Full Size	Mid-Size	Small Size
Power Requirement Reduction			
Weight reduction	8.0%	7.0%	.0%
Rolling resistance reduction (radial tires)	2.5	2.5	2.5
Aero drag reduction	1.5	1.5	1.5
Accessory power	1.4	1.4	1.4
Driveline			
Extra gear or overdrive	4.0	4.0	4.0
4-speed auto transmission	8.7	8.7	8.7
4-speed auto transmission with lockup in all but low	12.0	12.0	12.0

Source: Reference 13.

Table VI-3

COMPOSITE FUEL CONSUMPTION REDUCTIONS FROM VEHICLE IMPROVEMENTS (Percent)

Source of Reduction	Vehicle Class Small	Subcompact	Compact	Large
1 "Intermediate" weight reduction	6%	10%	15%	18%
2 4-speed automatic transmission with lockup	3	6	7	8
3. Reduced acceleration[a]	2	2	5	10
4. Lower aerodynamic drag	3	3	3	2
5. Improved accessories and drive	1	1	2	3
Overall effect of intermediate improvements	14%	20%	29%	35%
6. Longer-term weight reduction (replaces item 1)	12%	21%	23%	25%
7. Continuously variable transmission [CVT] (replaces item 2)	10	13	14	15
Overall effect of longer-term improvements	26%	35%	40%	45%

a. Assumes an increase in 0-60 mph acceleration time ranging from 1 second for the small car class to 3 seconds for the large car class.

Source Reference 10.

There is disagreement in the literature as to when and which of these power plants will become available to the driving public. For example, H. E. Dark, in his book, *Auto Engines of Tomorrow*, expects light-duty diesel and stratified-charge engines to be the first available alternatives. CalTech's Jet Propulsion Laboratory (JPL), in a study performed for Ford Motor Company entitled *Should We Have A New Engine?*, gives the nod to improved conventional engines in the near term and to gas turbine and Stirling power plants in the longer term. Perhaps the discrepancy can be attributed to differences in points of view. Dark's choices were based on state-of-the-art (i.e., with the technology available, which engine could be placed on the market first?). Each propulsion system is considered by itself, and no assumptions pertaining to extraordinary research and development are made. In contrast, the JPL study attempts to answer the question, "What should be done in the near future to improve the automobile, from the standpoint of society's needs and problems?" The objective of the study is to determine which technologies, existing or not, should be developed and manufactured so that (1) petroleum consumption is minimized; (2) air pollution is minimized; (3) benefit to automobile manufacturers is maximized, and (4) present automobile characteristics are not sacrificed. Objective (4) is achieved by analyzing each alternative on an "Otto-Engine-Equivalent" basis, i.e., vehicles powered by these engines would have characteristics (accommodations, performance, range) identical to a conventional Otto-engined car. All power plants are *compared* on this Otto-Engine-Equivalent basis.

The first part of this section is primarily descriptive. The principles and problems of each alternative engine are discussed. The comparative characteristics of the engines follow. The reader should remember, however, that differences in opinion do exist among automotive experts.

<u>Stratified-Charge Engine</u>. The stratified-charge engine is a relatively new version of the spark-ignited internal combustion power plant. The major difference between it and the conventional engine is in the method of fuel delivery to the combustion chamber.[5]

> "A stratified-charge system is a method of feeding an internal combustion engine some form of heterogeneous fuel-air mixture that is changeable, so that the engine is always being fed the correct recipe for its need of the moment."

For instance, leaner mixtures could be delivered while the car is cruising; passing maneuvers or uphill climbs require richer air-to-fuel ratios. With stratified-charge, the character of this ratio is quite flexible. Both piston and rotary engines can operate on the stratified-charge principle.

Honda's CVCC is presently the only car available that offers this unique combustion process. The CVCC has two carburetors, and an auxiliary combustion chamber for each cylinder. One carburetor measures out a rich mixture to the small, auxiliary combustion chamber, while the other carburetor supplies the main combustion chamber with an extremely lean fuel charge. A spark plug fires the rich mixture and the flamefront travels into the main chamber, firing the otherwise unignitable lean mixture. The resultant mixture is very lean compared to that which is fired in a conventional internal combustion engine.[4]

Variations of this process exist. Texaco, Southwest Research Institute, and the Ford Motor Company have developed single-chamber units (in comparison to Honda's dual-chamber system). The technique employed with these involves swirling the intake charge in a cylindrical combustion chamber so that the mixture is rich near the center and lean on the periphery. Careful aiming of the intake charge and precise control of intake air are key factors in this process.[4,12]

The most important characteristics of the stratified-charge engine are allegedly modest improvements in emissions and fuel consumption but there are indications that when the stratified-charge engine is adjusted to be as good or better in all pollutants than the best of the current Otto cycle engines, the fuel advantage is essentially lost.

<u>Light-Duty Diesel Engine</u>. The diesel engine is an internal combustion engine which differs from the current gasoline engine in its manner of fuel ignition. Bryant explains:[2]

> "The diesel is a high-compression engine with air as the working fluid. Fuel is injected near the end of the compression stroke and is ignited by the heat of compression."

The most distinct difference between the gasoline engine and the diesel engine is air-fuel ratio. While Otto cycle engines cannot be operated much leaner than stoichiometric, diesel power plants will not run efficiently at richer than stoichiometric.[12]

Since the diesel engine ign-tes itself, there is no need for an electric ignition system or items such as spark plugs, distributors, condensers, points, and high tension cables. Fuel is injected directly into the cylinder so there is no carburetor.

Diesel-powered automobiles have been in existence for over 50 years. In Europe, where gasoline is very expensive, diesel cars make up a significant percentage of the passenger vehicle fleet. In America, the diesel is not so popular. Speed- and performance-wise, it is inferior to the automobile powered by Otto cycle gasoline engines.

When cars equipped with Otto cycle and diesel engines are compared on a basis of equal performance, the fuel advantage of the diesel in miles

per British thermal unit (Btu) is reduced to about 10%. (Part of the well-known fuel economy advantage of the diesel is due to the higher heat content of a gallon of diesel fuel compared to gasoline.)

Gas Turbine Engine. The automotive gas turbine engine is based on the Brayton cycle.[10]

1. Compression of the working fluid from ambient pressure to elevated pressure.

2. Addition of heat to the working fluid at the constant elevated pressure.

3. Expansion of working fluid back to ambient pressure, with extraction of useful work.

Over 30 years of research and development has been devoted to the automotive gas turbine. Chrysler Corporation alone has built six generations of turbine power plants, each one an improvement over its predecessor. The consensus among automotive experts is that the gas turbine can be developed to meet energy and pollution constraints.

A simplified schematic of how the gas turbine operates is provided in Figure VI-6. Intake air passes through the air compressor, where the pressure is increased. This compressed air then goes through the regenerator, a key component which transfers heat from the exhaust to the intake air. The hot, compressed air is then heated further in the burner. The initial increment of work is extracted from it in the compressor turbine. This turbine turns a shaft powering the air compressor. More work is done as the slightly cooled airstream passes through the power turbine. This component supplies torque to the transmission. After the power turbine, the jet gives up a sizable portion of heat in the regenerator, then flows out of the system as exhaust.

The "free turbine" engine has just been described. It stands in contrast to the "single shaft" turbine, in which the compressor and power turbines are located on the same shaft. Single-shaft turbines are less complicated than free turbines, but require the use of complex, continuously variable transmissions in order to match the narrow speed range of the engine to the broad range of speed demanded by the drive shaft.[10] The operating speed range of free turbines is not restrictive, and conventional transmissions can be used.

Most of the current research effort is devoted to turbine blades. Presently, metallic components which impose an upper temperature limit are being used. If turbine inlet temperature could be increased by 100°F, 6% and 14% improvements in fuel economy and specific output, respectively, would result.[4] This and more could be realized through the development of ceramic turbine blades. Perfection of these silicon carbide components would constitute a major breakthrough. Cheap mass production techniques must evolve for this to be completely successful.

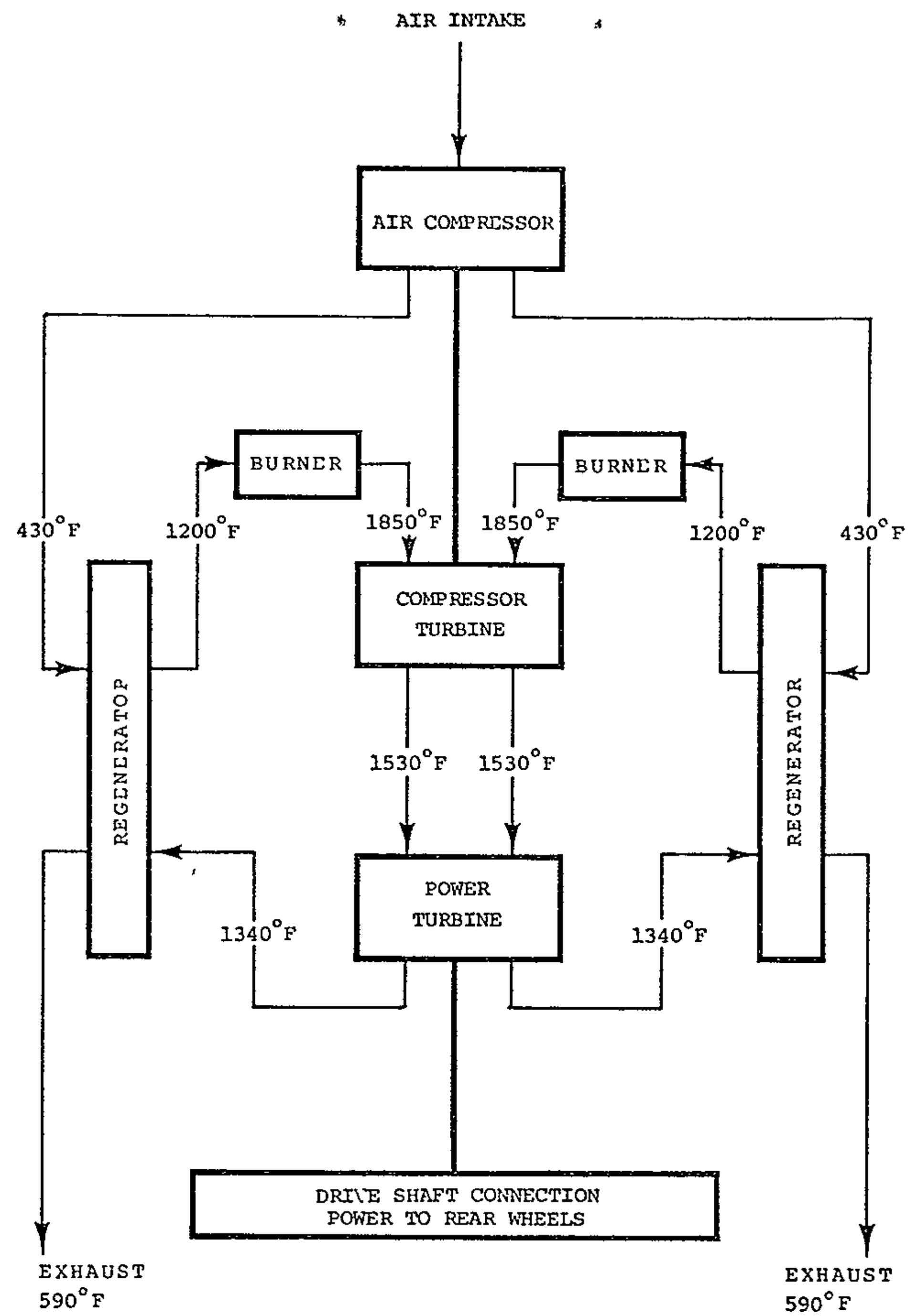


Figure VI-6. SIMPLIFIED SCHEMATIC OF SIXTH GENERATION CHRYSLER GAS TURBINE ENGINE[6]

The advantages of gas turbines are low emissions, low power plant weight, and good fuel economy at high or cruising powers. The basic disadvantage is poor economy at idle and low powers. The latter problem can be solved if turbine inlet temperatures can be increased using ceramic blades.

Steam (Rankine Cycle) Engine. Steam-powered vehicles operate on the external combustion principle, and are rather uncomplicated in design. The working fluid is heated to a vaporized state, performs work in the engine, and is converted back to a liquid state in the condenser. Then, it is pumped back to the boiler to be reused. This process is known as the closed, or Rankine cycle. In contrast, the undesirable "open" cycle releases spent steam to the atmosphere.[4]

The external combustion principle mentioned above deserves a brief explanation. It simply implies that the working fluid is heated outside of the chamber where work is performed. In an internal combustion engine (the everyday gasoline engine), a fuel-air mixture is introduced into the cylinder, is ignited, and does work in the "power" stroke. In a Rankine cycle engine, the working fluid is first heated, and then introduced into the expander.

There are two types of expanders being developed for steam engines: piston and turbine. The piston configuration will be quite similar to those in gasoline-powered internal combustion engine cars. The turbine expander is light and compact, like its gas-fired counterpart, but should present few materials problems because temperatures are at least 600°F cooler than those in a gas turbine. Experts believe that the piston expander is the more feasible alternative, due to its wider speed range of efficient operation. Also, the piston engine is capable of high efficiency at part load; the turbine expander runs best at maximum power. Since passenger cars are usually operated at light loadings, the reciprocating piston expander probably would be employed until a turbine-type is optimized.[1,8]

Water is the working fluid being studied the most for use in an external combustion engine car. Water is abundant, inexpensive, and chemically stable to high temperatures. It also has attractive and well-defined thermodynamic properties.[1] In spite of all these marvelous features, one objectionable feature of water practically ruins the entire system--it freezes at 32°F. Many attempts to decrease the freezing point by blending in chemicals have failed because they detract from performance. In colder climates, the only solution may be to insulate the engine compartment or provide a small pilot burner to keep the feedwater warm.[8] Draining the tank is feasible, but impractical.

But why use water if one cannot depend on it year-round? This is the philosophy behind the move to manufacture a synthetic working medium. For instance, Thermo-Electron Corp. is developing "Fluorinal-85" (F-85), a compound consisting of 85 mole-% trifluorethanol, 15 mole-% water. Fluorinal-85 has exhibited good thermodynamic properties at low temperatures (500°-600°F). This allows the use of low cost normal carbon steels

in engine blocks. Also, lubricants can be mixed right into the fuel. Best of all, this noncorrosive liquid has a freezing point of -82°F.

Synthetic working fluids unfortunately face some very serious problems. To begin with, most thermodynamically acceptable media are expensive (F-85 will cost $0.90 to $1.35 per pound); therefore, fluid loss must be eliminated for practical power plants. These fluids also tend to be chemically unstable, decomposing after prolonged exposure to modest temperatures. The exhaust from an organic turbine is super-heated, adding the necessity and complexity of more heat exchange capability. Organic cycles also require higher fluid flow rates than steam cycles, calling for pumps with higher power requirements and larger flow areas in heat exchangers. Finally, it is necessary to consider the frightening consequences of the combustion of organic fluids. Should they accidentally come in contact with flame, a highly toxic phosgene gas would be generated.[1,2,8] All these negative factors must be rectified in order to make the organic "vapor" turbine a feasible alternative.

The advantage of the Rankine cycle is low emissions. Because of poor efficiency, however, it is probably the least attractive of the alternatives.

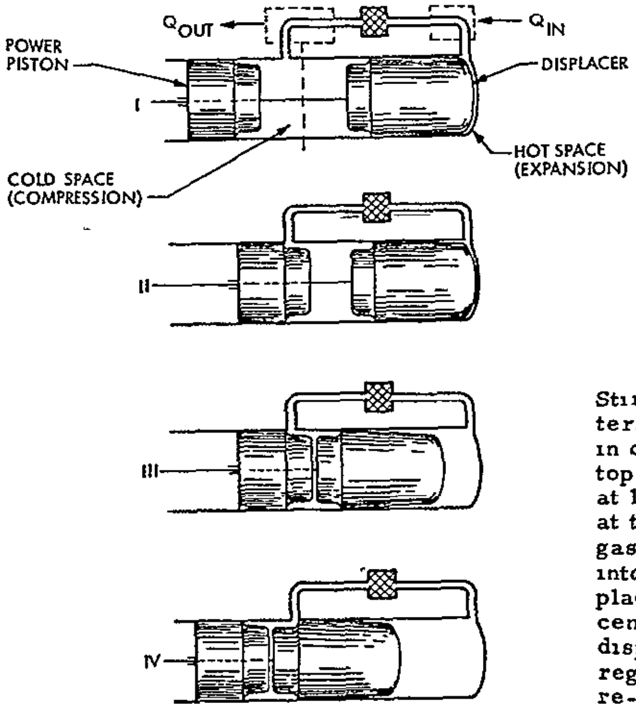
<u>The Stirling Engine</u>. The final combustion power plant to be considered is the Stirling engine. Like the Rankine, it is an external combustion engine based on a closed cycle.

A Scottish clergyman, Reverend Robert Stirling, invented the original Stirling in 1816. Low-pressure air was used as the working fluid. The multipurpose engine was used in a variety of applications until it was superseded by smaller, more efficient steam, electric, diesel, and gasoline power plants.

Philips of the Netherlands renewed work on the Stirling in 1938. Philips has licensed many other companies interested in development of the Stirling. It has been shown that the Stirling's efficiency is potentially higher than the best internal combustion engines. The automotive Stirling engine will be slightly larger than a conventional engine, but will be much quieter.[4]

The Stirling cycle consists of four phases, depicted in Figure VI-7. The operation of this engine is extremely complex. For the sake of brevity, the cycle is explained in the drawing. By alternately heating and cooling the working fluid (usually hydrogen), work can be extracted as the gas expands (Step IV).

The Stirling engine offers the promise of low emissions and high fuel efficiency. Its operating temperatures are extremely high and materials requirements are severe.



Piston displacer diagram showing Stirling cycle. I. Piston at bottom dead center. Displacer at top dead center All gas in cold space. II. Displacer remaining at top dead center Piston has compressed gas at lower temperature. III. Piston remaining at top dead center. Displacer has shifted gas through cooler regenerator and heater into hot space. IV. Hot gas expanded. Displacer and piston have reached bottom dead center together. With piston stationary, displacer now forces gas through heater, regenerator and cooler into cold space, thus re-attaining situation I

Source: Reference 10.

Figure VI-7. STIRLING CYCLE

The Electric Vehicle. At the turn of the century, electric vehicles were quite popular in the United States. The electric vehicle's most remarkable characteristic--simplicity--was valued highly by the public. Its propulsion system consisted of two components, a set of batteries and a DC traction motor. Thus, there were never any starting problems or difficulties with a clutch, and driving was very simple.

The electric's major disadvantage then, as now, was its limited range and speed. Early models rarely exceeded 25 mph or a range of 50 to 75 miles. As the "gas buggy" became relatively superior performance-wise, the electric lost its share of the market.

There are several issues in modern electric vehicle design. One objective is to minimize weight and friction. Prototype electric vehicle chassis are being constructed of aluminum with some steel reinforcement. Body material may also be aluminum or plastic. Reduction of rolling resistance is achieved by streamlined bodies and improved tire design. The major effort is being devoted to battery development. Specifically, two parameters--energy-density and power-density--must be increased so that the electric vehicle can provide a minimum level of service. Energy density (watt-hours/pound of battery) limits electric vehicle range,

power density (watts/pound of battery) places a constraint on acceleration. The present lead-acid battery system powering an electric vehicle has an energy density of 8 watt-hour/pound (30 miles at 30 mph). This must be increased fivefold to a minimum battery energy density rating of about 40 watt-hour/pound to achieve range and speed characteristics likely to be widely accepted.[11]

Sodium-sulfur (Na-S), lithium-chloride (Li-Cl), and zinc-air (Zn-air) batteries are being developed as power sources for future electric vehicles. Zn-air and Na-S units will take a long time to perfect. The former has many complicated components; the latter operates at 300°C, so a way must be found to constantly maintain this temperature. Na-S and Li-Cl batteries appear to have higher energy densities compared to Zn-air (100 vs 70); however, in a mature state, all will enable a car to travel 150 to 200 miles under turnpike or city driving conditions.[11]

Comparison of Alternative Automotive Propulsion Systems

The following discussion concerning the comparative characteristics of alternative automotive propulsion systems is based on information obtained from the previously mentioned Jet Propulsion Laboratory study entitled, *Should We Have A New Engine?* The data used in the study is recent, and the analysis is thorough. An unusual feature of the JPL study is the comparison of alternatives on an Otto-Engine-Equivalent (OEE) basis, i.e., vehicles with various power plants are compared after engine size selection to give performance in each case equivalent to the Otto cycle engine vehicle.

Before presenting the comparisons, it is necessary to define a number of terms:

- UC Otto -- The conventional uniform charge Otto cycle spark-ignited internal combustion engine which burns a uniform mixture of air and fuel. Treats exhausts with catalytic or thermal converter. Baseline engine in analysis is equipped with a "3-way" catalytic converter, in order to comply with statutory emission standards. The vast majority of vehicles manufactured to date are included in this category.
- SC Otto -- Stratified-charge Otto cycle engine. Also uses exhaust converters.
- Single-Shaft Brayton -- Brayton cycle gas turbine with compressor and turbine mounted on a single shaft. Requires a continuously variable transmission.
- Free Turbine Brayton -- Free turbine Brayton cycle gas turbine engine.

OEE	-- Otto-Engine-Equivalent. An OEE vehicle, by definition, has an alternate power plant which meets the expectations of its class, as derived from current buyer acceptability criteria. Relative to the UC Otto, an OEE alternative has identical passenger and luggage accommodations, identical accessories, identical aerodynamics (except for engine-induced changes), identical range, equivalent performance (based on 10-second acceleration distance and 0-60 mph time), and equally acceptable driveability, safety, durability, and noise level.
Mature Engine	-- Near-term improvement of engine as limited by present technology.

Weight and Horsepower Comparisons of OEE Vehicles. Table VI-4 illustrates curb weights and design maximum horsepower ratings of the vehicles powered by alternative engines. The data indicate that a Brayton-powered automobile is capable of similar performance (relative to UC Otto) at reduced weight and horsepower.

A Stirling car weighs about the same as the UC Otto but has a lower power output. The diesel is heavier than the UC Otto, but its power output has been made about the same through the installation of turbochargers (devices which supply more air to the combustion chamber).

Fuel Quality Requirements of OEE Vehicles. Fuel requirements for the UC Otto, SC Otto, and diesel vehicles are relatively strict. The two Otto cycle cars have historically obtained power by burning gasoline. Only recently has an attempt been made to determine the feasibility of other liquid hydrocarbon fuels (methanol, methanol-gasoline blends, ammonia, etc.). Diesel oil appears to be the optimal fuel for the compression-ignition process.

The Brayton, Stirling, and Rankine engines which operate on continuous combustion principles, can tolerate a broader range of liquid hydrocarbons. Methanol, ethanol, gasoline, kerosene, and diesel oil are just some of the possible fuels. According to Dark, "even brandy or French perfume will work!"[12] This fuel flexibility must be considered as an advantage of the continuous combustion power plants.

Table VI-4

WEIGHT AND HORSEPOWER OF OTTO-ENGINE-EQUIVALENT VEHICLES WITH MATURE ENGINES

Engine Type	Small: Curb Weight (lb)	Small: Design Maximum Power (hp)	Compact: Curb Weight (lb)	Compact: Design Maximum Power (hp)	Full-Size: Curb Weight (lb)	Full-Size: Design Maximum Power (hp)
UC Otto (baseline)	2,100	70	3,100	125	4,000	175
SC Otto	2,110	70	3,150	127	4,090	179
Diesel	2,310	74	3,340	131	4,220	182
Brayton (single shaft)	1,880	49	2,660	86	3,400	118
Brayton (free turbine)	1,920	51	2,710	89	3,470	123
Stirling	2,140	57	3,050	99	3,890	137
Rankine	2,220	66	3,200	119	4,130	166

Source: Reference 10.

Fuel Economy of OEE Vehicles. A comparison of the fuel economies of mature OEE vehicles is presented in Table VI-5. From observation of sales-weighted averages, one sees that Stirling engines provide the best fuel economy. The single-shaft gas turbine is second with the "free turbine," gas turbine, diesel, and stratified-charge vehicles showing lesser gains compared to the reference 1975 fleet. The single-shaft gas turbine requires a continuously variable transmission. JPL's analysis indicates that the mature steam-powered automobile will get virtually the same fuel economy as the typical 1975 car.

Table VI-5

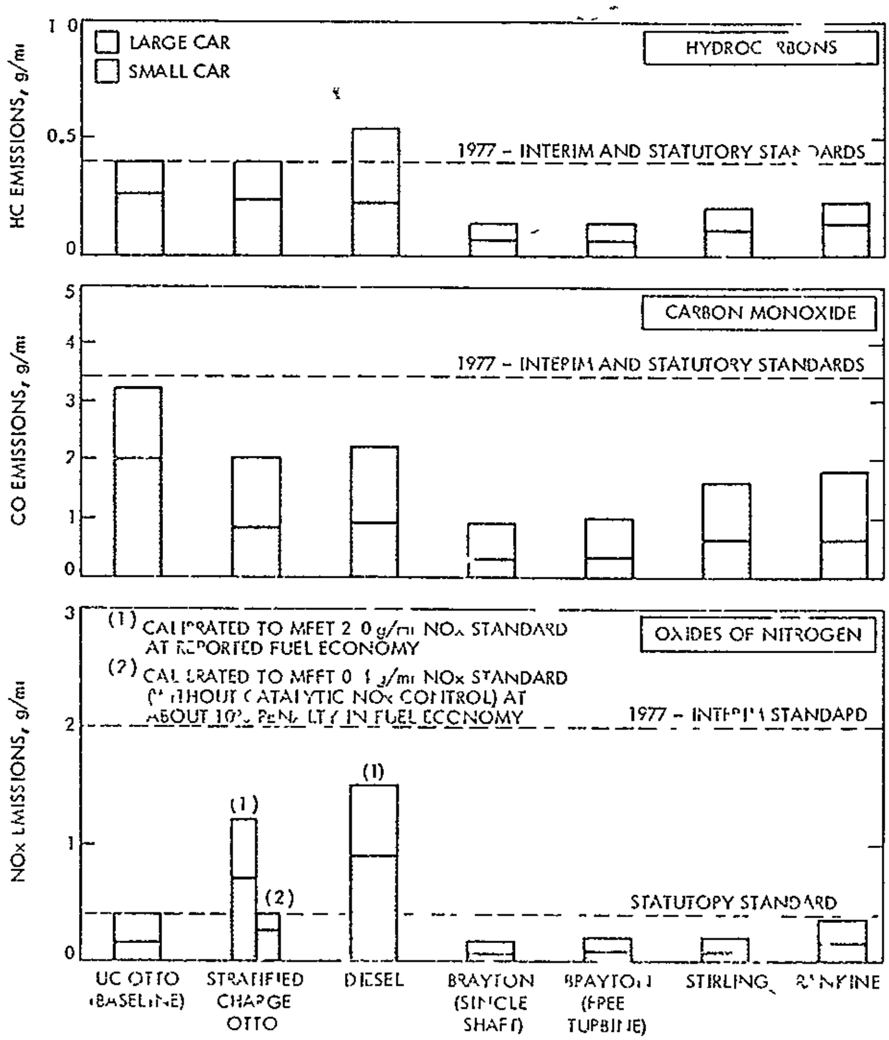
FUEL ECONOMY OF OTTO-ENGINE-EQUIVALENT VEHICLES
WITH MATURE ALTERNATE ENGINES[a]
(Miles/Gallon, Gasoline Equivalent)

Engine Type	Vehicle Class: Small	Compact	Full-Size	Sales Weighted Average (present market)
UC Otto (baseline)	30	21	17	17.2
SC Otto[b]	32	23	18	18.6
Diesel[b]	32	23	19	19.5
Brayton (single shaft)	34	27	22	22.7
Brayton (free turbine)	31	24	20	20.5
Stirling	39	30	25	25.2
Rankine	25	19	15	15.6
Average 1975 cars (reference)	26	19	15	15.6

a. 55% urban, 45% highway driving cycle fuel consumption. Present vehicle technology.
b. Calibrated to meet 2.0 g/mi NO_x standard.

Source: Reference 10.

Exhaust Emissions of OEE Vehicles. Figure VI-8 presents a listing of hydrocarbon, carbon monoxide, and oxides of nitrogen exhaust emissions for OEE vehicles. Stirling and Brayton cycle engines again are superior to the other alternatives. The otherwise inferior Rankine cycle engine is in the same class with Stirlings and gas turbines--all three comply with 1977 EPA statutory air quality standards. The JPL study states that, with difficulty, diesels could meet the 0.41 gram/mile HC standard. Also, large versions could achieve 1.0-1.5 gpm NO_x; however, the 0.4 gpm NO_x level is unattainable.



Source: Reference 10.

Figure VI-8. COMPARISON OF EMISSION LEVELS FOR MATURE ENGINE VEHICLES

<u>Manufacturing Cost Differentials of Mature OEE Vehicles</u>. The unit cost differences of mature alternate power systems are depicted in Table VI-6. Alternative engines are equivalent to a full-size 175-horsepower UC Otto.

It appears that the free turbine Brayton, Stirling, and Rankine power plants will have significantly higher unit costs than the UC Otto and other alternatives. A major impediment to the implentation of any of these new cycles is the huge current investment in tooling for the Otto

engine and high cost of replacing it. The research and development required to eliminate technological risk before commitment to production will be expensive and time-consuming.

Table VI-6

UNIT COST DIFFERENCE OF MATURE ALTERNATE POWER SYSTEMS[a]
(Per Engine, in 1974 Dollars)

Engine Type	Performance-Equivalent Horsepower	Manufacturing Cost Increment	Amortized Tooling Cost Increment	Power System Total Cost Increment
Baseline UC Otto (reference)	$175	$ 0	$ 0	$ 0
UC Otto[b] (oxidation catalyst only)	175	-40	0	-40
SC Otto	179	25	15	40
Diesel	182	145	15	160
Brayton (single shaft)	118	20[c]	40	60[c]
Brayton (free turbine)	123	170	90	260
Stirling	137	200	70	270
Rankine	166	360	60	420

a. Increment above cost of baseline Otto engine; full-size class, Otto-Engine-Equivalent vehicles. All costs are based on 400,000 units per year. Estimates rounded to nearest $10.
b. Mature UC Otto engine with only an oxidation catalyst system to meet 2.0g/mi NO_x standard.
c. Includes cost of special transmission (CVT), which is estimated to be the same as that of the conventional 3-speed automatic transmission used by all other engines.

Source: Reference 10.

Initial Retail Purchase Price Differentials for Mature OEE Vehicles. The initial retail purchase price differentials of mature OEE vehicles are presented in Table VI-7. "Sticker prices" exhibit a trend similar to the one associated with manufacturing costs: the diesel and the continuous combustion engines, except for the single-shaft Brayton, significantly increase vehicle selling prices.

Table VI-7

INITIAL RETAIL PURCHASE PRICE DIFFERENTIAL FOR MATURE OTTO-ENGINE-EQUIVALENT VEHICLES[a]
(Per Vehicle, in 1974 Dollars)

Engine Type	Vehicle Class: Small	Compact	Full-Size
Baseline UC Otto (reference)	$ 0	$ 0	$ 0
UC Otto[b] (oxidation catalyst only)	-50	-50	-50
SC Otto	-10	50	90
Diesel	70	190	260
Brayton (single shaft)	50	0	-30
Brayton (free turbine)	140	180	230
Stirling	200	270	300
Rankine	280	430	560
Typical 1974 Car Retail Price[c]	2,700	3,200	4,100

a. Increment above baseline vehicle.
b. A mature UC Otto vehicle using oxidation catalyst only to meet 2.0 g/mi NO_x.
c. To nearest $100.

Source: Reference 10.

Ownership Cost Differential for Mature OEE Vehicles. Table VI-8 is a listing of "out-of-pocket" cost differentials for mature OEE vehicles. The data indicates that the Brayton and Stirling are much cheaper to operate than the baseline UC Otto. This is mainly a result of higher fuel economies and the ability to operate on a variety of low-cost hydrocarbon fuels. A smaller, yet significant cost savings is also available with the diesel. High initial costs and poor fuel economies make the Rankine cycle engine unacceptable.

Electric Vehicle Comparisons. The comparison of three electric cars with two Otto engine vehicles is presented in Table VI-9.

It is worthwhile to describe the three battery systems considered in the analysis. The lead-acid battery represents current state-of-the-art in electric vehicle power systems. The energy available from a set of lead-acid batteries has constrained electric vehicle utility to short-haul, low-speed operations. The nickel-zinc battery is an advanced version, achievable with present technology--a "mature" battery. Its use as a power source would definitely improve electric vehicle performance. The sodium-sulfur battery is an advanced version still in the development phase. This battery has the "potential" to put electric vehicles on an equal footing with heat engine vehicles, performance-wise.

Table VI-9 indicates that electric vehicles are heavier than comparable Otto engine vehicles and have considerably smaller ranges. Driving cycle fuel economies are similar; Otto engine vehicles get considerably better mileage at a 60-mph cruise.

The validity of comparing exhaust emissions is questionable. Whereas heat engine vehicles could be considered as line or area sources, electric vehicles are point sources. In other words, electric vehicle pollution comes from the electrical generating plant and not the tailpipe. It is also important to mention that the emissions figures are for oil-fired power plants. A coal-fired plant would produce more pollution, especially SO_x and particulates; a nuclear power plant would produce none of the pollutants listed.

Energy Summary

The sum of the vehicle improvements indicate fuel consumption reductions of 14% to 35% in the short term and 26% to 45% in the longer term. When added to the engine fuel economy gains, total fuel usage reductions of the order of 40% to 50% can easily be anticipated. Note that the above gains are not algebraically additive and in some cases not cumulative, e.g., the single-shaft gas turbine gain included a continuously variable transmission. Nevertheless, the overall fuel consumption reduction of 40% to 50% corresponds to improvements in fuel economy (miles/gallon) of 67% to 100%. Considering the likelihood of a shift to smaller cars, i.e., full-size to compact, etc., a national fuel economy improvement of

Table VI-8

OWNERSHIP COST DIFFERENTIAL FOR MATURE OTTO-ENGINE-EQUIVALENT VEHICLES[a] (Per Vehicle, in 1974 Dollars)

	Vehicle Class					
	Small		Compact		Full-Size	
Engine Type	35,000 Miles,[b] 3 Years	Life Cycle, 100,000 Miles in about 10 Years	35,000 Miles,[b] 3 Years	Life Cycle, 100,000 Miles in about 10 Years	35,000 Miles,[b] 3 Years	Life Cycle, 100,000 Miles in about 10 Years
Baseline UC Otto	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
UC Otto (oxidation catalyst only)[c]	- 50	-150	-100	-200	-100	-200
SC Otto[c]	- 50	- 50	0	- 50	50	0
Diesel[c]	- 50	-150	- 50	-150	0	-150
Brayton (single shaft)	-150	-300	-250	-600	-350	-850
Brayton (free turbine)	- 50	-150	-100	-300	-150	-450
Stirling	-100	-250	-150	-450	-200	-600
Rankine	150	350	250	400	350	550
Reference Cost[d] of Typical 1974 Vehicle	3,500	8,400	4,300	9,700	5,700	11,700

a Present value at 7% annual discount rate, 52¢/gallon gasoline, 49¢/gallon diesel fuel, and 48¢/gallon broad-cut fuel All incremental costs rounded to the nearest $50 Increment above baseline vehicle (negative numbers represent saving to alternate vehicle owner)

b This approximates the ownership cost to the first owner and is based on an assured constant resale percentage (for each car class) In actuality, the high fuel-economy, low-maintenance car would be expected to have higher resale value and look even more attractive

c Calibrated to meet 2 0 g/mi NO_x standard

d Including depreciation, fuel, maintenance, insurance, garage, parking, tolls, and taxes Data from DOT estimates with our adjustments for depreciation, fuel, and present value calculations Rounded to the nearest $100

Source Reference 10

Table VI-9

ELECTRIC VEHICLE COMPARISONS

	Battery Systems			"Comparable" Otto Engine[a]	
	Lead-Acid	Nickel-Zinc	Sodium-Sulfur		
Otto Engine Horsepower	---	---	---	40	80
Electric Motor Horsepower (peak)	40	85	85	---	---
Traction Battery Weight (lb)	960	1,090	1,090	---	---
Vehicle Curb Weight (lb)	2,900	3,230	3,500	1,960	2,100
10-sec Acceleration Distance (ft)	335	370	445	285	405
50-mph range, 6% Grade (mi)	6	60	55	215	230
Driving Cycle[b] Range (mi)	30	145	235	445	325
Driving Cycle[b] Fuel Economy (mpg)[c] (with regenerative braking)	35	32	31	37	27
60-mph Fuel Economy (mpg)[c]	26	25	25	33	29
Emissions[d] (g/mi)					
HC	0.03	0.03	0.03	0.41	
CO	0.04	0.04	0.04	3.4	
NO_x	0.44	0.48	0.49	0.4	
SO_2	0.91	0.99	1.02	0.15-0.20	
Particulates	0.09	0.10	0.10	0.15-0.40	

a. Non-Otto-Engine-Equivalent performance.
b. Based on SAE J 227 metropolitan driving cycle (consumes about the same energy as the EPA urban driving cycle)
c. Equivalent energy consumption at the electrical generating station.
d. Equivalent emissions based upon an oil-fired electrical generating plant. The emissions of NO_x, SO_2, and particulates would be higher with a coal-fired plant, and all emissions of these pollutants are zero with a nuclear plant.

Source Reference 10.

of about 90% or more is reasonable. The most likely long-term power plants are the gas turbine (Brayton cycle) and the Stirling engine.

An Appraisal of the Conclusions

The preceding discussions can be considered as reasonable statements of the automobile energy and pollution problems, a comprehensive listing of the vehicle and engine design alternatives, and a correct indication of the size of the overall energy efficiency gains that can be expected in the future. The precise benefits from each technological development are less clear and, above all, the likelihood of achieving reliable, efficient, and cost-effective solutions to the material design and technological problems of a particular power plant is quite speculative.

In a critique by the Ford Motor Company (December 15, 1975) of the JPL report, *Should We Have A New Engine?*, upon which much of the above discussion is based, the JPL authors are accused of showing a bias. The particular bias is said to be that which restrains optimism about near-term developments about which much is known, but becomes very optimistic about future power plants about which little is known. The JPL report is said to have a "very good correlation between lack of knowledge about an engine and high expectations for the engine."

Our conclusion should be that there is excellent likelihood of improved, reliable, economic performance from both advanced versions of Otto cycle engines and new engine alternatives but that which of the alternatives will be the winner is speculative. Energetic pursuit of technological solutions for all of the promising alternatives should be encouraged.

Alternative Fuels--Methanol-Fueled Spark-Ignited Internal Combustion Engine

Alternative fuels for automobiles are much discussed. These include methanol and hydrogen. The economic and energy drawbacks of hydrogen were noted in Section III of this report; here, the discussion will focus on methanol.

An internal combustion engine designed to operate on methanol-based fuels would be virtually identical to one that burns gasoline; the reciprocating, four-stroke cycle is unchanged.

There are two methods currently existing for methanol production--pyrolysis and extraction from coal. Pyrolysis is a process involving anaerobic decomposition of cellulosic, carbonanceous urban wastes. Projected yields are approximately 71 gallons per ton of waste.[3] Methanol can also be produced from coal at an efficiency of 60% to 70%.[9] Plans have been formulated for 19 regional coal-fed plants which would output 730 million barrels of methanol per year, from 111 million tons of coal. This would amount to 20% of the annual tonnage mined.[6]

As mentioned before, a methanol fuel would be "neat" (100% methanol) or blended with gasoline. Regardless of form, this fuel would have certain properties requiring special treatment:

- Methanol dissolves great amounts of water. Such contamination can cause phase separation and misfire. A new distribution system would have to be developed that prevents water intrusion. Fouling of methanol-based fuels in on-board tanks would be arrested by venting with a dryer.

- Methanol fuels corrode lead, magnesium, and aluminum components. Improved materials technology (e.g., resistant plastics) will eliminate this problem.

- Methanol has a latent heat of vaporization four times that of gasoline (i.e., much more heat must be provided to the intake charge in order to vaporize it). This indicates a need for carburetor and intake system revisions.

- Methanol's volume energy density (heat of combustion) is half that of gasoline; therefore, cars operating on pure methanol would require double-size fuel tanks in order to carry equivalent amounts of energy.[6,7]

Engine performance with methanol-gasoline blends is generally favorable:

- The addition of methanol boosts octane. A 10% blend has a Research Octane Number 4-1/2 units higher than that of straight gasoline.

- Methanol's high latent heat of vaporization cools intake air, increasing its density and mass flow, and yielding as much as a 10% increment in power.

- Blends containing up to 40% methanol do not cause cold-start problems.

- Fuel economy remains constant on an energy (miles per Btu) basis.[6]

Performance difficulties with methanol/gas blends are vapor lock and reduced driveability. The introduction of alcohols into gasoline causes fuel to boil at the fuel pump inlet, limiting flow to the carburetor (vapor lock). It is felt that vapor lock could be prevented by adjusting the mixture's volatility at the refinery, or by blending fuel at the pump.

A test program on six 1971 cars indicated that the addition of methanol to gasoline caused objectionable driveability characteristics (e.g., hesitation and surge). The problem here is that 1971 cars operate with very

lean (air to fuel) ratios, and methanol/gas blends require slightly rich A/F ratios.[6] Therefore, carburetors will have to be readjusted and recertified before such a fuel can be used.

The performance outputs of automobiles operating on 100% methanol are varied. On the one hand, methanol-powered cars exhibit better driveability characteristics and fuel economy (in miles per Btu) than gas-powered cars when air/fuel ratios are properly adjusted. However, it is impossible to start the engine below 60°F unless a small auxiliary gas tank is provided.[6]

Safety

Regulation of the consumer has been difficult. For example, the regulation requiring seat belt interlocks to the ignition was overturned by Congress after public outcry. This implies that major safety innovations, whether originating with the manufacturers, or through the spur of regulation, will have to take due account of convenience and public opinion.

During the next few years, we expect a gradual trend in auto design toward an integral, hardened inner shell for the passenger compartment; adequate padding and simpler restraint devices, such as the inertial seat belt; and impact absorbing and crushable exterior design.

The problem for safety conscious auto designers will be in reducing the weight penalty of innovations when increased weight means increased energy usage.

Automatic Control Systems

An intriguing concept which arises from the highway guideway being already available is an "autopilot," which on freeways would relieve the driver of his duties and allow a decrease in accidents caused by driver error. Two versions have been considered based on either radar or laser sensing systems. Otherwise they are quite similar. On the highway a reflecting stripe is put down the middle of lanes, probably the innermost, "fast" lane only. After entering the highway, centering the vehicle over the stripe and pushing the button, the control system would take over. It would keep the car centered over the stripe and by splitting the beam, and also chopping or pulsing it, the control system would measure the speed and distance of the vehicle ahead. The control minicomputer would maintain a safe distance, and provide acceleration and braking, including emergency braking, as needed.

In its early conception, the intention of the automatic control was to allow higher speeds, with safety, while on automatic control. Speeds around 100 mph (160 kph) were mentioned, a level where radial tires can still function adequately without the excessive tire wear that stock

cars experience at 180 mph. Also the "autopilot" concept was intended to increase the modal split for automobile intercity transportation. Such a unit would cost, in mass production, a minimum of $500; it would be especially compatible with a stoichiometric air-fuel control system.

The value of the "autopilot" will probably be decided by other, social issues. The 55-mph speed limit and, desires by energy conservationists to reduce the automobile modal split, make its cost effectiveness questionable.

User Costs for Automobile Transportation

Cost factors for automobiles disaggregate in a fashion different from other modes. The guideway cost is implicitly included in the direct operating cost through the gasoline taxes set aside for highway construction. Further, from the viewpoint of most owners of automobiles, they would have to own the car anyway, whether or not it is being driven for any particular trip. Thus, the decision as to whether or not the auto will be used on a trip is based on the "perceived cost," the cost of gas, oil, and maintenance costs. Since the sales weighted average for fuel consumption is about 15 miles per gallon for continuous driving, and maintenance costs are about 2.5¢ per mile, the perceived cost is about 6.5¢/mile.

If we examine the total cost of owning an automobile, then an average figure of about $1,500 per year or 15¢/mile (which is also the IRS figure) was computed assuming a six- to eight-year ownership period. Those costs, for a standard sedan, disaggregate approximately as shown below:

Category	Percent of Total Annual Cost
Gas and oil	28%
Initial cost and interest	41
Maintenance	17
Insurance	14
	100%

The deviations from the above average figures are roughly ±50% depending on the tastes and habits of the owner.

Noise

The nature of the noise produced by automobiles and trucks is nearly identical to that produced by intercity buses. Below are typical noise levels measured at 50 feet from the vehicle.

Vehicle	Speed (mph)	dBA
Automobile	40-59	67
	50-59	72
	60-69	73
Diesel	40-49	84
Tractor Trailer	50-59	85
	60-69	88

Sources. Serendipity, Inc., *A Study of the Magnitude of Transportation Noise Generation and Potential Abatement*, U.S. DOT Report No. OST-ONA-71-7, November 1970. Vols. I, III, IV, V.

Department of the California Highway Patrol, *Noise Survey of Vehicles Operating on California Highways*, July 1971.

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The main sources of highway noise are tires, engines, and aerodynamic noise. At low speeds engine noise predominates, while at higher speeds, tire noise is the major contributor.

Possible noise reductions over time are as follows:

Vehicle	dBA Reductions by 1975	1980	1985
Automobiles (standard)	2	4	5
Sports, compact, and imported automobiles	2	7	10
Trucks	3	8	10

Source: Wyle Laboratories, *Transportation Noise and Noise From Equipment Powered by Internal Combustion Engines*, U.S. Environmental Protection Agency Report No. NTIO 300.13, December 31, 1971.

Intercity Bus Technology

J. C. Prokopy
Peat, Marwick, Mitchell & Co.

Brief Description of Physical and Operational Features

The intercity bus system consists of privately owned vehicles with private maintenance bases, operating between privately owned (for the most part) terminals using public highways. Since buses normally constitute less than 1% of the vehicles on public highways (although they account for about 5% of the passenger-miles), they are constrained to operate within the regulations applied to the operation of similar vehicles on public facilities, unless separate rights-of-way are developed. Thus, permanent 55-mph speed limits on public highways could severely restrain the ability of the bus to compete with nonhighway modes apart from the technological speed capability of the vehicle or right-of-way. Conversely, the introduction of automated highways would be beneficial to buses without any serious commitment on the part of the bus mode, since such facilities would likely have to be justified for reasons other than intercity bus movement.

Likely Developments in Vehicle Technology

The most important technological development for the bus mode in the foreseeable future should be implemented within the next two to five years. Eight intercity buses are currently outfitted with turbine engines for test purposes. Fuel economy has been brought within the range of diesel consumption and the turbines already meet the 1977 air pollution and noise level regulations. They provide a much quieter ride for the passenger, free of the customary engine vibration. Currently being implemented is the reduction in the number of seats by one row for greater leg room. Also being introduced on new buses is an automatic transmission (with direct drive in high gear). Most other potential developments are presently restricted by state and federal regulations. Bus companies have been pressing for legislation to allow six-inch wider buses (and hence seats) on interstate highways. Recent tests by the Federal Highway Administration have shown that the wider buses are as safe as current-width buses. Wide buses have been operated for some time in local service where allowed. Longer buses, such as articulated vehicles, have been designed, but their use is generally restricted. Operators have shown little interest in them because of the difficulty for the one driver to satisfactorily monitor passengers and the possible need to rebuild terminals to allow for maneuvering and to accommodate the longer vehicles at loading gates.

Amenities such as an on-board hostess and beverage service have been available on some routes and are being introduced on others A higher level of service such as three-across seating does not appear to be

warranted in light of the one-third increase in operating costs per seat-mile it would entail.

Operating Costs

Bus vehicle-operating costs are shared by both passengers and package express service. Since package express generates about one-sixth of the revenue, one-sixth of the operating costs could be allocated to that service. In fact, in scheduled service, package express generates a slightly greater share of the revenue since charter service rarely carries package express. The greater profitability of express would probably offset this in developing costs, hence Table VI-10 is based on assigning five-sixths of vehicle operating costs to passenger service. Costs are for a 40-seat bus. Average load on intercity buses in 1973 was 19.8 passengers

Investment Costs

The only significant investment component in bus operations, given that the highways are available, is the vehicle itself, currently ranging from about $80,000 for standard intercity coaches (new) to $118,000 for Greyhound's new Supercruiser with turbine engine.

Station costs can range from $100,000 for a small suburban station to over $1,000,000 for larger terminals. Major maintenance bases would cost several hundred thousand dollars, although a company the size of Continental Trailways has only about six such facilities.

Energy Requirements

Typical intercity buses consume about one gallon for every six miles at 55 mph; thus, at 140,000-Btu/gallon, they use about 23,000 Btu per mile, or 570 Btu/seat-mile.

Noise Emission

Typical noise emissions for intercity buses at 50 feet are

Speed	Noise
50-60 mph	81 dBA
60-70 mph	84 dBA

There are three main sources of bus noise: tires, engines, and aerodynamic noise At low speeds, the predominant noise source is the engine,

while at higher speeds, tires become the dominant source. Tire noise is greatly affected by the road surface. In the high frequency range, smooth asphalt produces less noise than concrete. The variance in tire noise levels due to road surface composition is roughly 7 to 10 dBA. New mufflers are a simple yet effective way of reducing engine noise, and the development of turbine engines should also reduce this noise level. Streamlined designs reduce aerodynamic noise at highways speeds.

Table VI-10

DIRECT AND INDIRECT OPERATING COST
(1973 Dollars)

	Cost per Seat-Mile	Percent Distribution
Direct Operating Cost Items		
Driver Wages	$.00467	48.4%
Maintenance	.00244	25.3
Fuel (1974)	.00078	8.1
Other Trans. Expense	.00099	10.3
Vehicle Depreciation	.00076	7.9
Total Direct	$.00964	100.0%
Indirect Operating Cost Items		
Station Operation	$.00294	37.2%
Overhead	.00195	24.7
Op. Taxes & Licenses	.00138	17.4
Ticketing and Advertising	.00055	7.0
Insurance	.00069	8.7
Op. Rents	.00040	5.0
Total Indirect	$.00791	100.0%
Total Operating Cost	$.01755	

Source: National Association of Motor Bus Owners, 1973 and 1974 data, Class I Motor Carriers.

Predictions of possible noise reductions yield these results

Vehicle	dBA Reductions by 1975	1980	1985
Highway buses	3	8	10
City buses	2	5	8

Source: Wyle Laboratories, *Transportation Noise and Noise from Equipment Powered by Internal Combustion Engines*, U.S. Environmental Protection Agency Report No. NTIO 300.13, December 31, 1971.

Air Pollution Emission

Typical air pollution emissions for diesel engines in bus service are:

Unburned Hydrocarbons	0.53 $lb/10^3$/seat-mile
Carbon Monoxide	0.23 $lb/10^3$/seat-mile
Nitrogen Oxide	0.86 $lb/10^3$/seat-mile
Sulfur Dioxide	0.16 $lb/10^3$/seat-mile
Particulates	0.43 $lb/10^3$/seat-mile

Block Speeds

Since highway speeds are limited now and for the foreseeable future to 55 mph, the block speed will necessarily be less than that. It is reasonable to assume a block speed for intercity buses of about 50 mph.

Safety

Recent bus accident rates for intercity operations are (1970-72, per 100,000,000 passenger-miles):

Passengers

Fatalities	0.09
Injuries	10.4

Nonpassengers

Fatalities	0.46 (automobiles, pedestrians, drivers)

This is slightly better than other common carrier modes, and substantially below automobile rates in all categories except other fatalities, where it is lower than rail, but higher than automobile or air.

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VII. OTHER GROUND TRANSPORTATION CONCEPTS

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VII. OTHER GROUND TRANSPORTATION CONCEPTS

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VII. OTHER GROUND TRANSPORTATION CONCEPTS

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Introduction

This chapter describes a collection of ground transportation concepts that did not fit in the other chapter categories. Some of the concepts represent complete systems that have some features that are advantageous, but also some features that make the concept not technically feasible or economically plausible at this time. They are cited here because the future may bring a research breakthrough that would remove the obstacle to implementation Some of the concepts are not complete systems, but represent interesting ideas that could be combined with other systems synergistically.[1,2] Finally, some modes are listed because they are important for freight transportation, if not for passenger transportation

Water Transportation

Although the modal split for water transportation of passengers is negligible (~0 3%), this is an important mode for freight.

Even with hydrofoil and surface-effect ships available in the future, no appreciable passenger water traffic appears likely. The energy requirements are too high There will always be specific locations where ferry service fulfills a local intercity need, and some nonbusiness vacation travel by water.

Pipelines

Pipelines for the transport of liquids such as oil, natural gas, or solids in slurry form are becoming increasingly important. The technology is well developed, standardized, and has the advantage of being able to operate at constant flow

Auto-Train Modes

There are a variety of concepts which involve carrying automobiles on a type of train. The Autotrain is a conventional rail system with special cars to carry automobiles and their owners which now travels from Washington, D.C., to Florida. It has not been as popular as Autotrain, Inc. would like. The problem appears to be in the waiting and scheduling of the auto-train interface. In the opinion of many potential users, if they are going to travel slowly by ground transportation and take their car, then they might as well drive the car and enjoy its freedom and convenience.

For high density corridors, several companies have proposed auto carrying trains, belts, or conveyors. As an example, Westinghouse proposed Roller-Road which had electrically powered wheels on which sled-like vehicles containing ten automobiles could travel. Each auto would load and unload from the side through vertical sliding doors. The cost, since a new powered guideway and new sled-vehicles are required, would be comparable to a TLV system. Speeds would be around 100 mph.

Present interest in these auto-train concepts is slight. The costs of such systems, when coupled with the terminal and interface problems, appear to offer worse service than the automobile or the train, separately, but at higher cost

Multimode Vehicles

The use of small, preferably battery-electric-powered, vehicles that would have a range of about 100 miles locally, and could also be used on an electrically powered guideway for intercity travel has been proposed. The problem lies again in the need for construction of a new special guideway, as well as in the necessity to buy or rent the special vehicles. If two cities could agree to underwrite the system on a rental basis, it might be possible. Otherwise, it does not appear to be competitive with other ground and air modes. Major proponents of this type of mode have been CALSPAN and Alden Self-Transit.

This system concept runs into the same difficulty as other concepts which require a special guideway such as urban personal rapid transit systems. Costs for such systems are running about $20 million per mile.

Tube and Vehicle Systems

There are several special ways that tubes and tunnels can be combined with vehicles. Although the costs would be prohibitive now, the ideas are clever enough to be discussed here in the event that at some future time the cost of tunneling drops sharply, as for example by application of high energy laser weapons to tunneling

A concept from Tube-Transit would combine a curved tunnel which descends and ascends sharply near stations so that the perceived acceleration to the passengers would remain at 0.1 g while the actual acceleration of the vehicle could be, say, 0.3 g. Vacuum propulsion is produced by pumping the air from in front of the vehicle while allowing normal atmospheric pressure behind it. The vehicles could be either rail or MAGLEV vehicles. The major problems with this concept are: (1) the need for deeper, and therefore more expensive, hard rock tunneling than for any other concept; (2) the impossibility of changing stations once the systems has been built, and (3) safety considerations on how to

remove a stuck or damaged vehicle from deep in the tube, when the tolerances must be close in order to use vacuum propulsion.

Another tube concept, also involving deep tunneling was proposed by RAND. Straight tunnels could be bored through the earth and partially evacuated. Then MAGLEV (repulsion) vehicles could run at speeds of 1,000 mph (1,600 kph) and yield coast-to-coast block times between city centers of three hours.

Again the problem with these novel ideas is guideway costs. With the Washington METRO, which uses cut-and-cover tunneling already exceeding $50 million per mile, such hard rock tunneling is economically impossible with today's tunneling technology A major breakthrough in tunneling technology would be needed to make these concepts viable.

Alternative Rolling Systems

A number of rolling systems which are alternatives to rail systems have been proposed. Monorail systems are less obtrusive than conventional rail systems, but offer slower speed, poorer ride quality, and comparable or higher cost. The Seattle and Disneyland Monorail systems provide two demonstration projects.

The cleverest of the alternative systems is the Overhead Rail proposed by several companies. By suspending the vehicle from overhead, it becomes self-banking on curves thus reducing the lateral accelerations to the passengers. A means of damping oscillations is required.

These systems' costs are comparable to those for TLVs, due to the need for special guideways, and offer less speed.

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